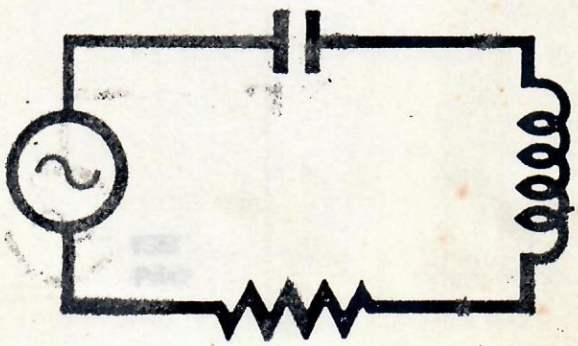
Ed-Lab
Text-Lab Manual
AC ELECTRONICS
PARTS G1 to G5



CES INDUSTRIES, INC.

Lab
3 MANUAL
ELECTRONICS
EXPERIMENTS G1 to G5

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Educational Products Division
130 Central Avenue
Farmingdale, New York 11735
Phone (516) 293-7430

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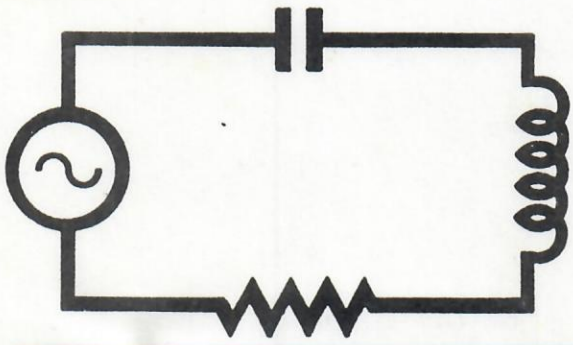
Ed-Lab
Text-Lab Manual
G1 - AC VOLTAGES and COMPONENTS



G1

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Ed-Lab
TEXT-LAB MANUAL
AC VOLTAGES and COMPONENTS
PART G1

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PART G1 - AC VOLTAGES and COMPONENTS

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STUDENT PROGRESS RECORD & GUIDE FOR AC PART G1

EXP./INFO.	TITLE	ASSIGNMENT		GRADE
		DATE DUE	DATE SUBMITTED	
	Safety Lesson			
Info. Sheet 1	Concepts of AC			
Experiment 1	Observing Effect of AC Voltages			
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Ed-Lab
TEXT-LAB MANUAL
AC VOLTAGES and COMPONENTS
PART G1

Safety Lesson

OBJECTIVES

When you finish this Information Sheet you will be able to:

1. List three general danger areas that may be encountered in Electrical and Electronics work.
2. List four possible effects of an electrical shock to the body.
3. List two ways to remove a shock victim from the power source.
4. Define Class A, Class B and Class C fires.
5. Specify the types of fire extingushers that can be used for electrical fires.
6. Identify True and False statements about hand tools.

DESCRIPTION

When working with electrical and electronic equipment there are several dangers that may be encountered. These are:

A. Electrical Shock
B. Electrical Fire
C. Hand Tool Injuries

In order to avoid these hazards, you will have to observe proper precautions and avoid irresponsible behavior. You must also learn to recognize dangerous conditions and report them to your instructor.

A. Electrical Shock results from contact with a source of electricity strong enough to stimulate the flexor muscles. Depending on the strength of the shock and its path through your body, it can cause you to:

1. Feel a tingling sensation
2. Jump back and break free
3. Freeze on the circuit, unable to let go
4. Stop breathing
5. Go into ventricular fibrillation, a condition where the heart beats wildly, out of rhythm, and so pumps little or no blood.

Conditions 3, 4 and 5 can lead to death unless treated immediately. Condition 3 requires that the victim be removed from the source of power as soon as possible and in a manner that does not endanger the rescuer. If you cannot turn off the power and remove the victim then use a jacket, shop apron, a long piece of wood, or any type of nonconductor to loop over the body and pull the victim loose. If the victim has stopped breathing begin artificial respiration immediately while someone goes for help. Artifical respiration is also required for conditions 4 and 5 above. See detailed instructions.

The Ed-Lab equipment has been designed so that it presents no shock hazard. Despite this, you should be careful, particularly when using other pieces of test equipment with the Ed-Lab 651.

Some basic rules for electrical safety are:

1. Do not perform electrical/electronic work in damp areas.
2. Do not assume power is off; check it.
3. Do not defeat safety switches (interlocks).
4. Do not remove the ground wire from equipment.
5. Do not use power plug adaptors (from 3 wire to 2 wire) to remove ground leads.

B. Electrical Fires that result from short circuits and overheating in electrical/electronic devices are listed as Class C fires. Only two types of fire extinguishers are to be used for electrical/electronic fires; Carbon Dioxide (CO_2) and Dry Chemical. See Figure 1.

C. Hand Tool Injuries - Electronics technicians use a wide variety of hand tools and some power tools to construct, repair and maintain equipment. If used improperly or in a careless manner the tools can cause injuries. The safe use of hand tools can be summarized in three statements. Use a tool properly. Use a tool only for the purpose it was intended. Keep all tools in good working condition.

Several important cautions for hand tools are:

Be careful when using soldering irons or soldering guns; they can cause painful burns and fires.

When using a wrench, pull on it rather than push.

Be sure hammer heads are tightly fastened to their handles before using them.

When using power tools, keep the line cord clear of the work.

Check the line cords of all power tools. Do not use if they have cracks or exposed wires.

When drilling, fasten the work so that it will not spin.

Be sure that all power tools have a 3 wire plug; do not use 3 wire to 2 wire adaptors to defeat the ground.

Wear safety goggles whenever the work produces flying chips.

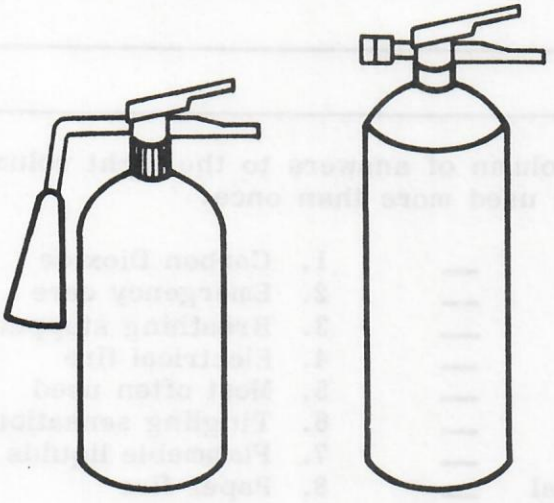


Figure 1 - Two types of fire extinguishers suitable for use in Class C fires (electrical/electronic). They may also be used for Class A fires (paper and rubbish) and Class B fires (flammable liquids such as oil, gasoline, paint, etc.). Because they can be used for Class A, B and C fires, they are very popular types of extinguishers.

ASSIGNMENT

1. List two ways to remove a shock victim from contact with an electrical circuit without endangering yourself.

   A. _____

   B. _____

2. List three dangers that may be encountered in an electronics laboratory.

   A. _____

   B. _____

   C. _____

3. Match the left column of answers to the right column. Answers may be used more than once.

A. Mild Shock	___	1. Carbon Dioxide
B. Class A	___	2. Emergency care
C. Class B	___	3. Breathing stopped
D. Class C	___	4. Electrical fire
E. Death	___	5. Most often used
F. CO_2	___	6. Tingling sensation
G. First aid	___	7. Flammable liquids
H. Dry Chemical	___	8. Paper fire

4. Indicate which of the following statements are True or False.

   A. It is safe to cut the ground pin off a 3 wire power plug when necessary. _____

   B. Clamp down any work that is being drilled. _____

   C. Soldering irons are one of the safest hand tools used by a technician. _____

   D. Safety goggles need not be worn if you already wear glasses for improved vision. _____

   E. Check all power cords before use. _____

FIRST AID FOR ELECTRICAL SHOCK

IF YOU OBSERVE AN ACCIDENT INVOLVING ELECTRICAL SHOCK,

DON'T JUST STAND THERE - DO SOMETHING !

RESCUE OF SHOCK VICTIM

The victim of electrical shock is dependent upon you to give him prompt first aid. Observe these precautions:

1. Shut off the high voltage.

2. If the high voltage cannot be turned off without delay, free the victim from the live conductor. REMEMBER:

   a. Protect yourself with dry insulating material.

   b. Use a dry board, your belt, dry clothing, or other non-conducting material to free the victim. When possible PUSH - DO NOT PULL the victim free of the high voltage source.

   c. DO NOT touch the victim with your bare hands until the high voltage circuit is broken.

FIRST AID

The two most likely results of electrical shock are: bodily injury from falling, and cessation of breathing. While doctors and rescue equipment are being sent for, DO THESE THINGS:

Control any bleeding by use of a pressure or a tourniquet.

Begin IMMEDIATELY to use artificial respiration if the victim is not breathing or is breathing poorly.

ARTIFICIAL RESPIRATION

1. Turn victim on back.

2. Clean the mouth, nose, and throat. (If they appear clean, start artificial respiration immediately. If foreign matter is present, wipe it away quickly with a cloth or your fingers).

3. Place the victim's head in the "sword-swallowing" position. (Place the head as far back as possible so that the front of the neck is stretched).

4. Hold the lower jaw up. (Insert your thumb between the victim's teeth at the midline - pull the lower jaw forcefully outward so that the lower teeth are further forward that the upper teeth. Hold the jaw in this position as long as the victim is unconscious).

5. Close the victim's nose. (Compress the nose between your thumb and forefinger).

6. Blow air into the victim's lungs. (Take a deep breath and cover the victim's open mouth with your open mouth, making the contact air-tight. Blow until the chest rises. If the chest does not rise when you blow, improve the position of the victim's air passageway, and blow more forcefully. Blow forcefully into adults, and gently into children.

7. Let air out of the victim's lungs. (After the chest rises, quickly separate lip contact with the victim allowing him to exhale).

8. Repeat steps 6 and 7 at the rate of 12 to 20 times per minute. Continue rhythmically without interruption until the victim starts breathing or is pronounced dead. (A smooth rhythm is desirable, but split-second timing is not essential).

DON'T JUST STAND THERE - DO SOMETHING !

Concepts of AC

INFO SHEET 1

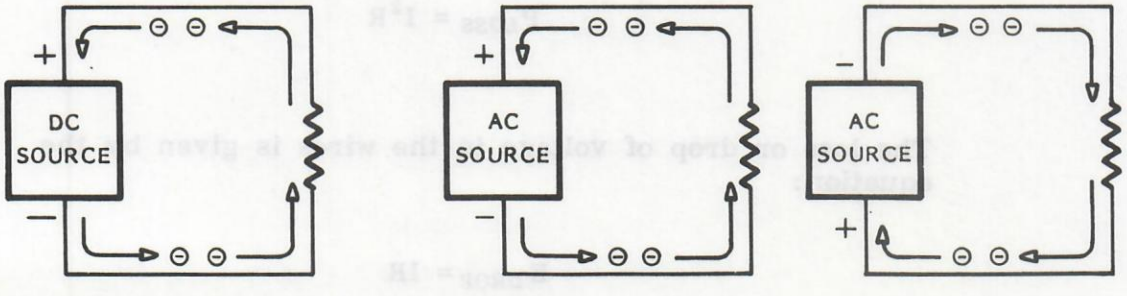
OBJECTIVES

When you finish this information sheet, you will be able to:

1. Define the problem in dc power distribution systems.
2. Calculate the power and voltage losses on the distribution lines of the system.
3. Explain how an ac power distribution system reduces power loss.
4. Describe the use of the transformer in ac power distribution systems.
5. Explain how an antenna radiates an electromagnetic field.
6. Describe the construction and explain the operation of a loudspeaker and earphone.
7. Define the ac terms, Frequency, Period, Amplitude and Wavelength.
8. Draw the circuit of a simple oscillator used to generate ac signals.
9. Explain the basic operation of the capacitor and diode in ac circuits.
10. Draw the sine, square, ramp and triangle ac waveshapes.

DISCUSSION

The letters AC stand for ALTERNATING CURRENT and are usually written as ac, AC or a-c. In dc circuits, the current is defined as flowing in one direction only as shown in Figure 1(a).



(a) DC FLOWS IN ONE DIRECTION (b) FIRST INSTANT SECOND INSTANT

Figure 1(a) - Dc current. (b) - Ac current flow.

In Figure 1(b), at one instant the ac current flows through the circuit in one direction. In the next instant the polarity of the ac source reverses and the current flows in the opposite direction.

Ac circuits are very important for many electrical and electronic devices and equipment including the distribution of electrical power, the transmision of radio and television signals and the generation of sound.

DC POWER DISTRIBUTION

Consider the power transmitted from a power generating station and delivered to several distant homes. This is illustrated in Figure 2.

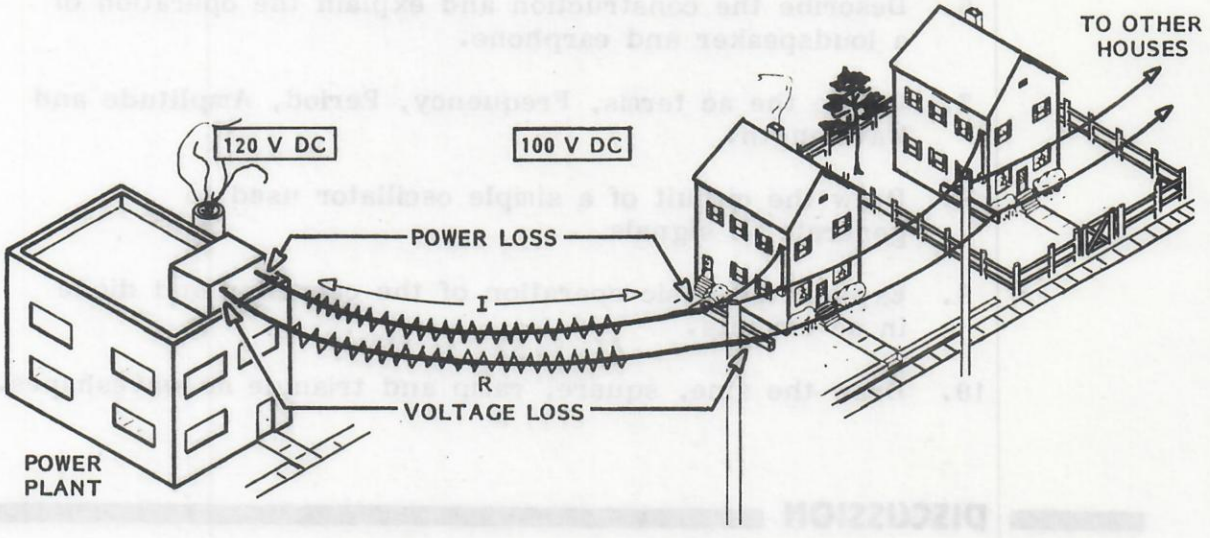


Figure 2 - Basic concepts of electrical power transmission.

The resistance of the wires is R and the current flow is I. The loss of power in the wires is given by the equation:

$$P_{LOSS} = I^2R$$

The loss or drop of voltage in the wires is given by the equation:

$$E_{DROP} = IR$$

If the total resistance in the transmission wires is only 1 ohm and the total current drain only 20 amperes, then:

LOSSES AT 120 V

POWER LOSS $P = I^2R$

$= (20^2)(1)$

POWER LOSS = 400 W

VOLTAGE DROP $E = IR$

$= (20)(1)$

VOLTAGE DROP = 20 V

It can be seen from the above calculations that the voltage delivered to the first home will not be 120 volts but rather 100 volts and still less to the homes further away.

In the early days of power distribution, the power plants generated 120 volts dc. The power plants were built close to the homes and the homes required only enough current to light a few lamps. But as power requirements increased and houses were built further away from the generating plants, the power losses and voltage drops increased to unacceptable levels.

To overcome this problem, a generator was considered for use that would produce an output voltage 100 times greater, 120 V x 100, or 12,000 volts. To deliver the same amount of power we would require 1/100th of the current or 0.2 amperes instead of 20 amperes over the same wires. The new power loss would then be:

LOSSES AT 12,000 V

POWER LOSS $P = I^2R$

$= (0.2^2)(1)$

POWER LOSS P = 0.04 W

VOLTAGE DROP $E = IR$

$= (0.2)(1)$

VOLTAGE DROP = 0.2 V

It is clear, now, that power and voltage losses are much less at higher voltages because less current flows. While the lower current drain would be an advantage, the use of 12,000 volts (12 kV) would, however, be very dangerous and would result in many accidental electrocutions in homes and factories.

There is no practical way to reduce 12 kV back down to 120 volts without generating even more losses than those we tried to avoid originally. It is for this reason that the power companies turned to ac which can be stepped up or down in value with little loss using a device called a TRANSFORMER.

AC POWER DISTRIBUTION

Actual practical power distribution systems operate with ac generators. As shown in Figure 3 below, the generator output is 5 kV.

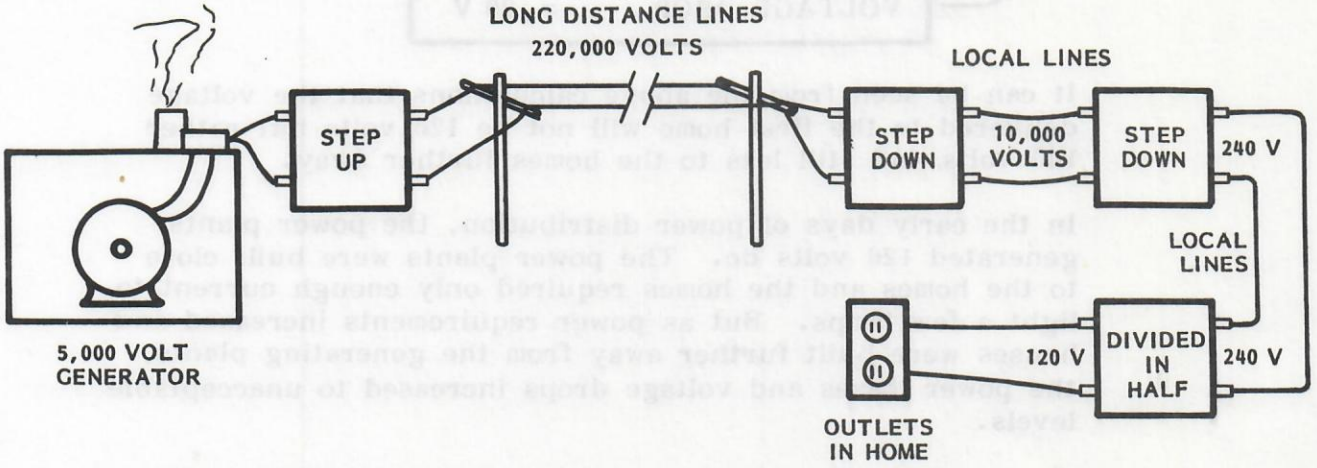
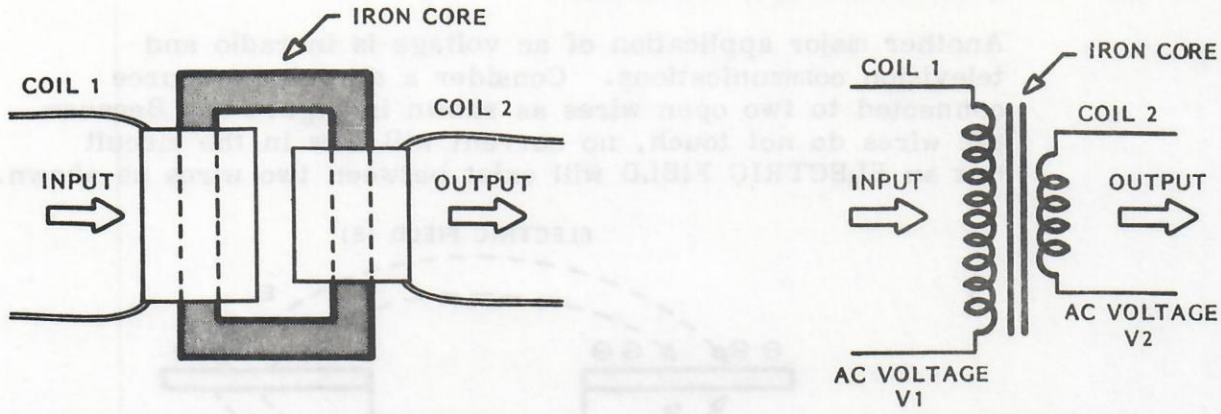


Figure 3 - Basic ac power distribution system.

The voltage generated at the power house is high, 5 kV. It is stepped up to 220 kV for long distance transmission and eventually converted back to 120 volts ac. These conversions, 5 kV to 220 kV to 240 V to 120 V, cannot be done using dc. Ac, with transformers, do this for us. Solid-State transistor systems provide future alternatives.

TRANSFORMERS

The conversions from low to high and back to low voltage ac is accomplished using a device called a TRANSFORMER. Transformers can only be used with ac which is why ac power generation is in use almost exclusively today. The operation of the transformer is based on electromagnetic principles. Consider two coils placed physically close to each other as shown in Figures 4(a) and (b). The two vertical lines in the schematic symbol indicate an iron core.

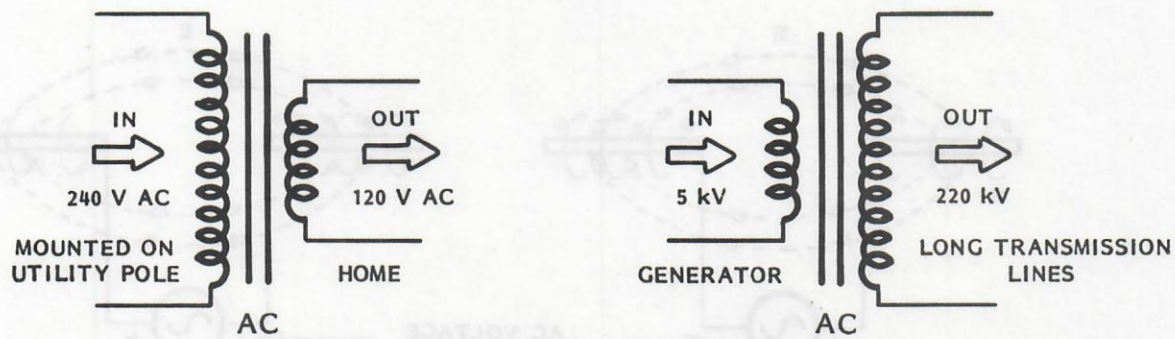


(a) TRANSFORMER CONSTRUCTION (b) TRANSFORMER SYMBOL

Figure 4(a) - Physical appearance of a basic transformer. (b) - Transformer symbol shows two windings and a core.

An input voltage and current flow creates a magnetic field around Coil 1. Because the current flow is ac, this magnetic field is constantly changing amplitude (strength) and direction. This changing magnetic field is coupled to Coil 2 through the core and the changing magnetic field induces a voltage in Coil 2.

The amount of voltage produced across Coil no. 2 is determined by the number of turns. If Coil 1 has 1,000 turns and coil 2 has 500 turns then the output voltage from Coil 2 will be half the input voltage to Coil 1. This is illustrated in Figure 5(a) and is called a STEP-DOWN TRANSFORMER. Details are given in Information Sheet No. 5.



(a) STEP-DOWN TRANSFORMER (b) STEP-UP TRANSFORMER

Figure 5 - Transformer variations.

If the output turns are greater in number than the input turns, the output voltage is greater, resulting in a STEP-UP TRANSFORMER. This is shown in Figure 5(b). Thus, we can see that the generation of ac, stepped up or down with transformers, makes possible the transmission of power over long distances.

AC IN RADIO AND TELEVISION

Another major application of ac voltage is in radio and television communications. Consider a dc voltage source connected to two open wires as shown in Figure 6. Because the wires do not touch, no current will flow in the circuit but an ELECTRIC FIELD will exist between two wires as shown.

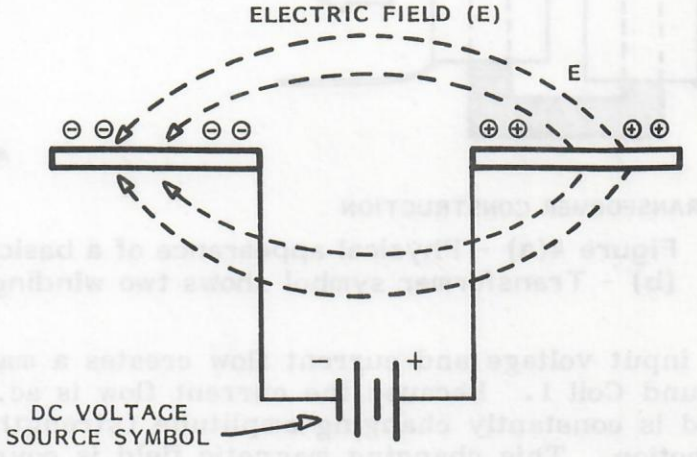


Figure 6 - The applied dc produces an electric field.

Now consider the effects of an ac voltage connected to the two wires, as shown in Figure 7. As the ac voltage reverses polarity, the electrons reverse direction and flow off one wire and onto the other wire. This occurs for each cycle of the ac voltage and is continuous as long as the voltage is applied.

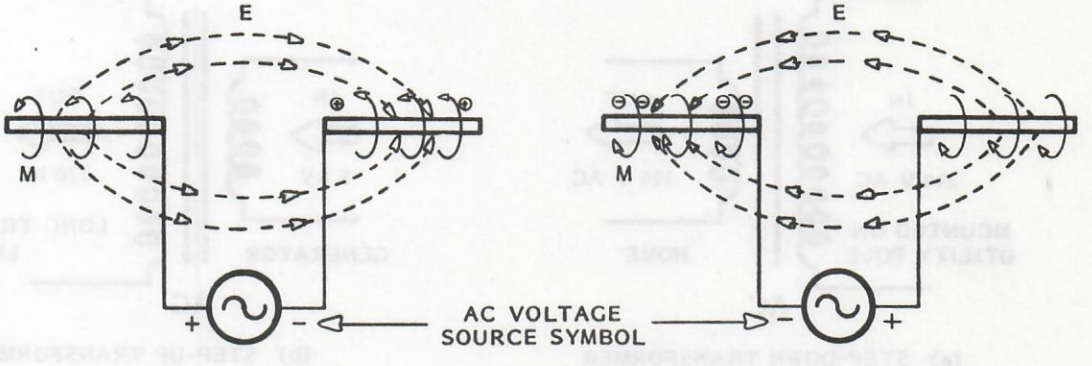


Figure 7 - Ac applied to the wire creates an electric and magnetic field.

When ac is applied to the two wires, electrons first flow into one wire but when they reach the end of the wire, they stop and rush to the end of the other wire when the polarity reverses. In addition to setting up an electric field (E), the electron flow also creates a magnetic field (M). As the ac voltage starts to reduce, the magnetic and electric fields start to shrink and draw back to the wires. The

lines of force, both E and M, that are farthest from the antenna do not draw back but break away. The next half cycle repeats the process and the following wave that breaks away is of opposite polarity, repelling the first wave which then starts to travel outward into the air. The combined field is called an ELECTROMAGNETIC FIELD. As shown in Figure 7 above, the E and M portions of the field are at right angles (90 degrees) to each other. Thus we now have an electromagnetic field radiated into the air that has the same voltage and variation properties as the ac voltage applied to the wires. The wires, when used in this manner, are called an ANTENNA and since the wires in Figure 7 are being used to launch the signal into the air, it is called a TRANSMITTING ANTENNA.

WIRELESS TRANSMISSION

The AC ELECTROMAGNETIC WAVES now travel through the air without the need of conducting wires. If another set of wires were placed in the air many miles away, the opposite effect will take place. The electromagnetic waves from the transmiting antenna will "hit" the RECEIVING antenna, inducing a voltage, as shown in Figure 8. In the early days of radio this was called WIRELESS transmission.

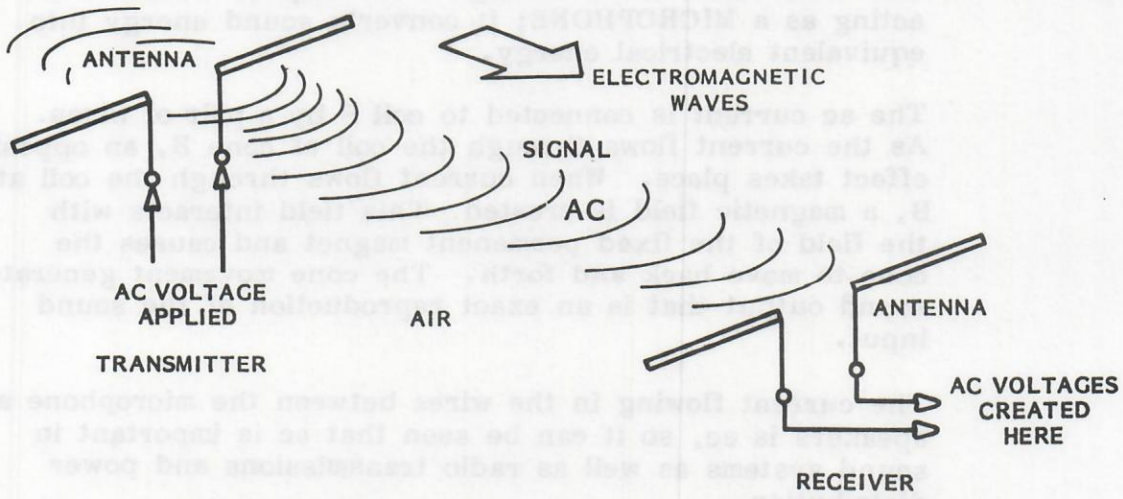


Figure 8 - Electromagnetic transmission.

By properly varying or "modulating" the ac signals, different information or "messages" can be transmitted. Examples are the voice and music of radio transmissions, television picture signals, computer data and so on. These are certainly outstanding applications illustrating why ac is so important.

AUDIO OR SOUND SYSTEMS

All sound, whether speech, music or noise, when converted by a microphone to their electrical equivalents, are ac voltages. Consider speaking into a cone as shown in Figure 9 below.

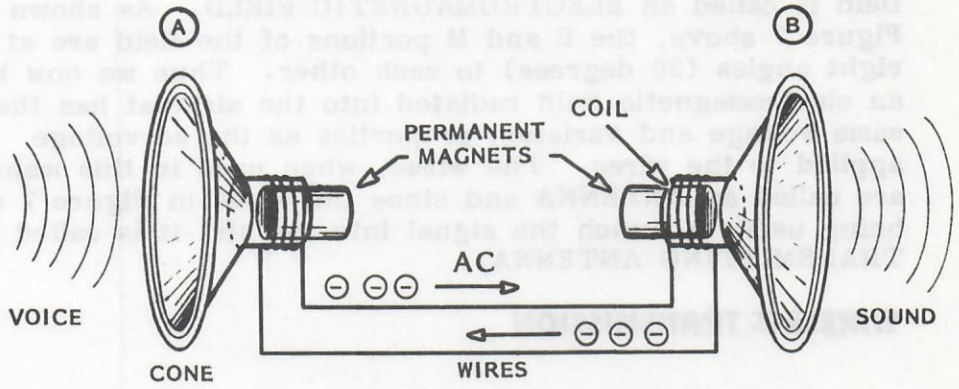


Figure 9 - Voice transmission by direct connection and ac currents.

The voice vibrates the air particles which then vibrate the cone. A coil of wire is attached to the cone, as shown, and a magnet is placed in the coil. As explained in Part F1 before, a wire moving in a magnetic field produces an electron flow in the wire. As the sound vibrates cone A back and forth, an ac voltage is developed. Cone A is acting as a MICROPHONE; it converts sound energy into equivalent electrical energy.

The ac current is connected to coil B by a pair of wires. As the current flows through the coil of cone B, an opposite effect takes place. When current flows through the coil at B, a magnetic field is created. This field interacts with the field of the fixed permanent magnet and causes the cone to move back and forth. The cone movement generates a sound output that is an exact reproduction of the sound input.

The current flowing in the wires between the microphone and speakers is ac, so it can be seen that ac is important in sound systems as well as radio transmissions and power distribution.

The cone and coil arrangement shown in Figure 9 is the basic design of a standard LOUDSPEAKER such as that in the Ed-Lab trainer.

EARPHONE/MICROPHONE

The earphone supplied with the Ed-Lab trainer operates in a manner similar to the speaker. Two coils are wound on the arms of a horseshoe magnet and are in series as shown in Figure 10. An iron disc or diaphragm is located close to the coils and magnet.

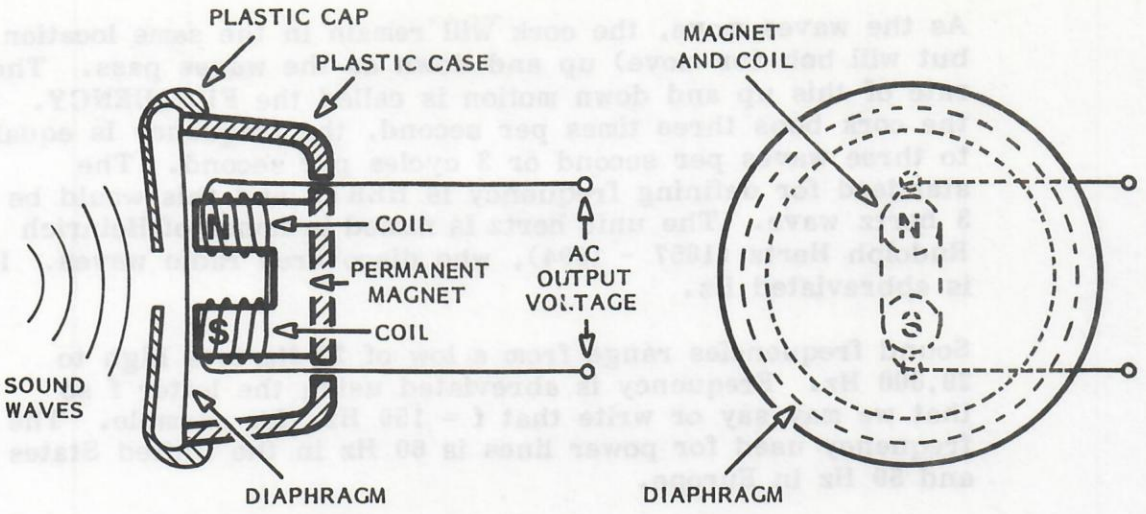


Figure 10 - Construction of the earphone/microphone.

The sound waves vibrate the iron diaphragm which changes the magnetic path. This causes the magnetic field in the coils to increase when the diaphragm moves close and to decrease when the diaphragm moves away from the coils. This results in an ac voltage developed across the coils that is equivalent to the sound input thus making the device a microphone.

The device shown in Figure 10 can also be used as an earphone which will convert electrical current into equivalent sound.

FREQUENCY

The ac sound signals generated by the microphone have a FREQUENCY and AMPLITUDE. To illustrate these, consider dropping a stone in a pool of water. You would observe waves flowing out from the drop point as indicated in Figure 11.

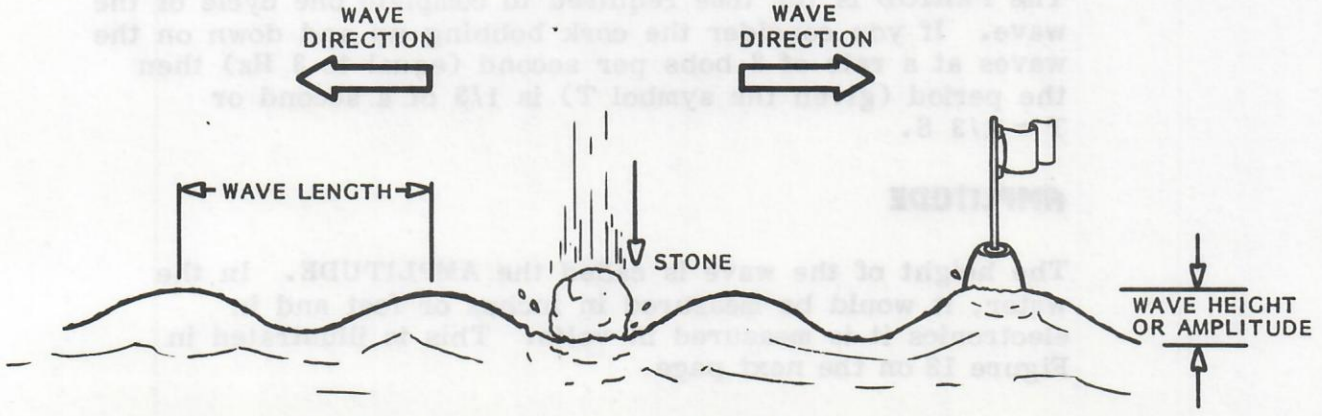


Figure 11 - Water anology describing ac waves.

As the waves move, the cork will remain in the same location but will bob (or move) up and down as the waves pass. The rate of this up and down motion is called the FREQUENCY. If the cork bobs three times per second, the frequency is equal to three waves per second or 3 cycles per second. The standard for defining frequency is HERTZ and this would be a 3 hertz wave. The unit hertz is named in honor of Heinrich Rudolph Hertz (1857 - 1894), who discovered radio waves. It is abbreviated Hz.

Sound frequencies range from a low of 20 Hz to a high to 20,000 Hz. Frequency is abreviated using the letter f so that we may say or write that f = 150 Hz, for example. The frequency used for power lines is 60 Hz in the United States and 50 Hz in Europe.

In sound waves, the frequency refers to the pitch we hear. As an example, consider the two sounds illustrated in Figure 12 below.

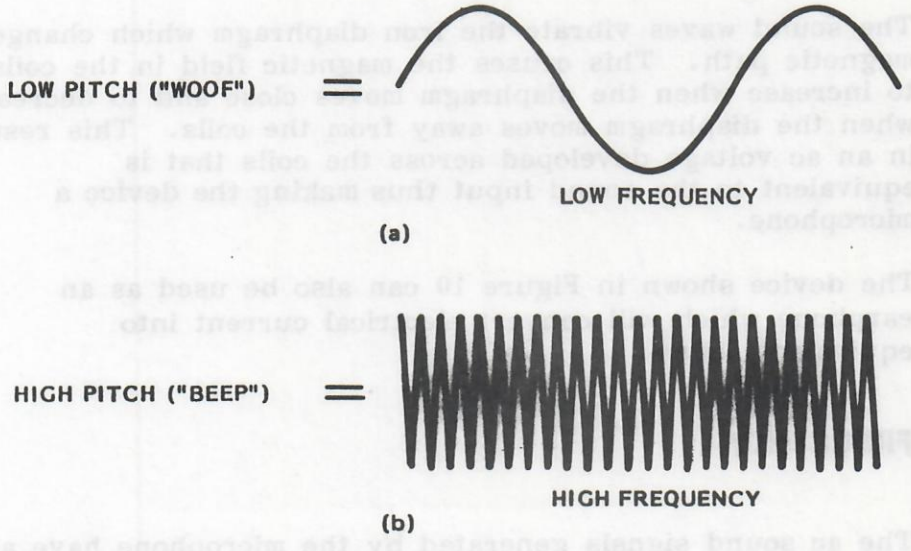


Figure 12 - Sound pitches.

PERIOD

The PERIOD is the time required to complete one cycle of the wave. If you consider the cork bobbing up and down on the waves at a rate of 3 bobs per second (equal to 3 Hz) then the period (given the symbol T) is 1/3 of a second or T = 1/3 S.

AMPLITUDE

The height of the wave is called the AMPLITUDE. In the water, it would be measured in inches or feet and in electronics it is measured in volts. This is illustrated in Figure 13 on the next page.

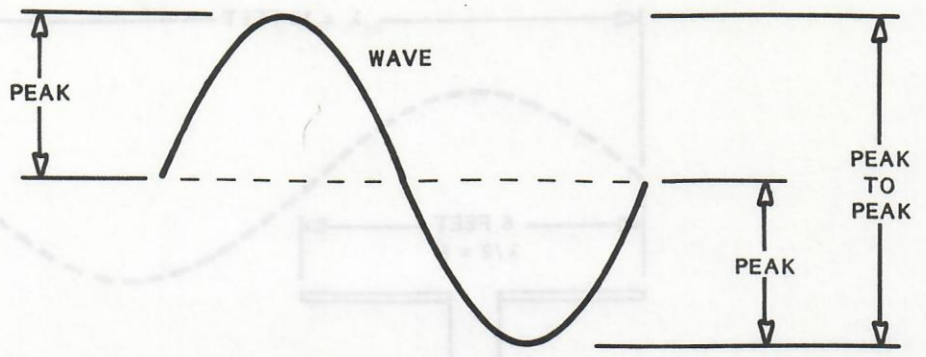


Figure 13 - Peak and peak-to-peak measurements of a wave.

The wave in Figure 13 is electrical and is measured in volts. If the peak is 2 volts then it may also be measured as 4 volts peak-to-peak. Peak and peak-to-peak are abbreviated as p and p-p.

WAVELENGTH

The WAVELENGTH or distance between peaks can measure several feet in the water analogy given in Figure 11. The wavelength of an ac voltage depends upon its frequency. The higher the frequency, the shorter the wavelength. Electrical wavelengths can measure as little as a fraction of an inch to miles in length. A 10,000 Hz (10 kHz) signal has a wavelength of 18.6 miles and an 880,000 (880 kHz) signal from radio station WCBS in New York has a wavelengh of 1,118 feet. Operating at a still higher frequency is TV channel 6 at 82,000,000 Hz (82 mHz). Its wavelength is 12 feet. Observe that as the frequency increases, the wavelength gets shorter.

The symbol for wavelength is the Greek letter LAMBDA, λ. Thus, it may be stated that

$\lambda_{\text{SOUND, 10 kHz}} = 18.6$ miles
$\lambda_{\text{RADIO WCBS, 88 kHz}} = 1{,}118$ feet
$\lambda_{\text{TV CHANNEL 6, 82 mHz}} = 12$ feet

Antennas that are used to receive electromagnetic signals work best if their length corresponds to the wavelength of the signal to be received. Since a full wavelength for most of the communication spectrum is very long, use is made of 1/2 or 1/4 wavelength antennas ($\lambda/2$, $\lambda/4$). A 1/2 wavelength antenna, a type called a DIPOLE, is shown in Figure 14.

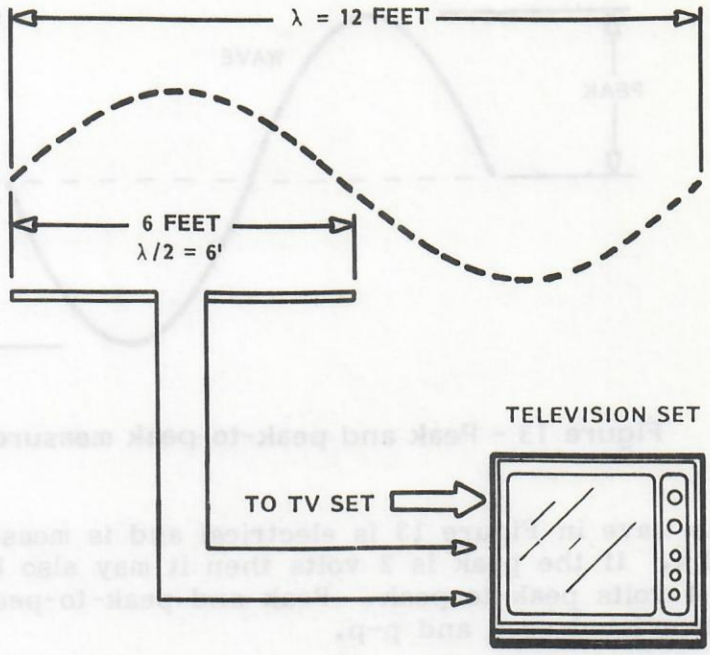


Figure 14 - Simple dipole antenna cut to 1/2 wavelength to receive channel 6 at 82 mHz.

If the dipole is to be used to receive channel 6, its wavelength should be, ideally, 12 feet. But 12 feet is too long for antenna elements to support themselves so a half wave is used and the required length is now 6 feet. We can see, then, that the size or length of the antenna is related to the wavelength of the ac voltage it must receive (or transmit). Antennas and wavelengths are discussed much later in Telecommunication studies.

POWER GENERATION

As previously stated, a coil made to move in a magnetic field will have a voltage induced into that coil. Ac power is generated using this concept as shown in Figure 15 where a most basic ac generator is shown.

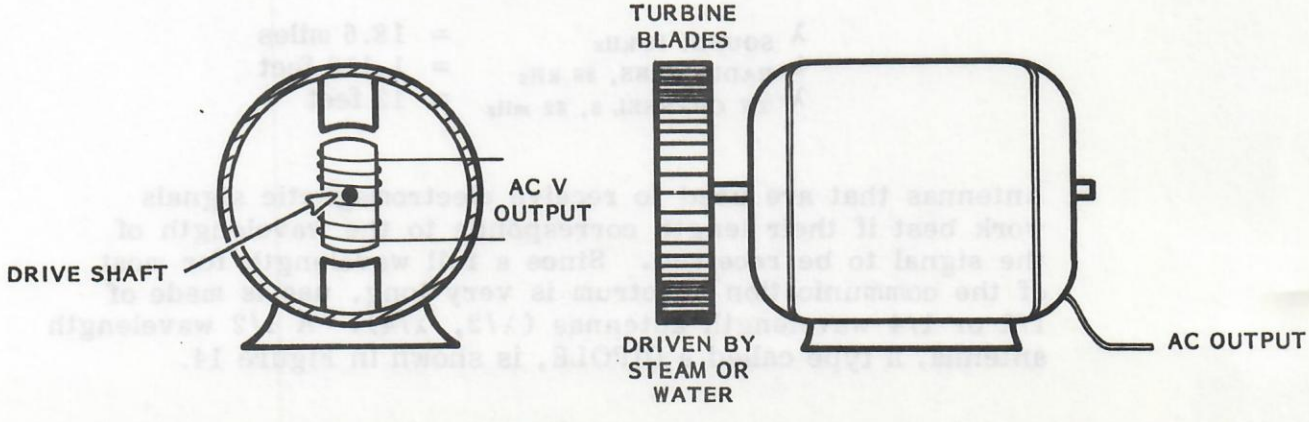


Figure 15 - Simplified ac generator concept.

Water or steam pressure drives the turbine blades causing the generator shaft to rotate. The shaft rotates the coil between the North and South magnetic poles to generate an ac voltage output. More detail on such generators is given later. A typical ac generator would produce 5,000 volts at 100 amperes and thus be capable of producing a power of:

$$P_{OUT} = E \cdot I$$

$$= (5,000)(100)$$

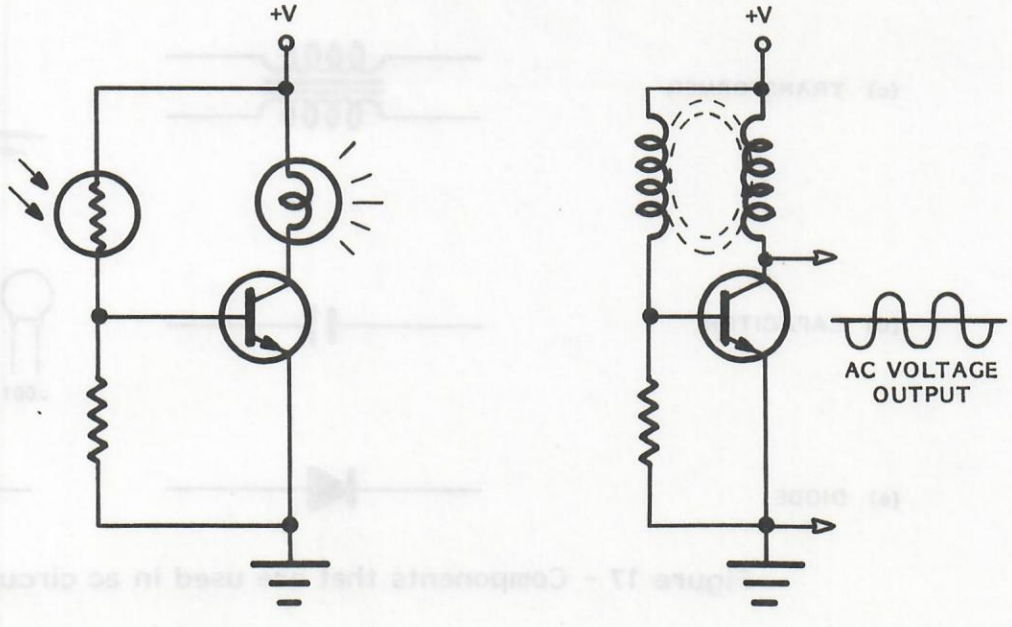
$$= 500,000 \text{ Watts or } 0.5 \text{ Megawatts}$$

Many power generators stand 25 feet high, 40 to 50 feet long and are capable of producing very high output power.

AC SIGNAL GENERATION (OSCILLATORS)

The ac voltage needed to produce radio or television transmissions require much less power than that generated by rotary devices for power distribution systems. These ac voltages, generated at much higher frequencies, are produced by electronic circuits that are much smaller than the rotary generators, often no larger than a peanut.

Recall an earlier circuit studied in Module 1, DC, that used a photocell and a lamp with a transistor shown in Figure 16(a).



(a) PHOTOCELL AND LAMP CIRCUIT (b) OSCILLATOR CIRCUIT

Figure 16 - Photocell circuit and ac oscillator circuit.

The transistor produces a current gain that allows the photocell to control the lamp intensity in Figure 16(a). A similar circuit is used to produce an ac output voltage in a circuit called an OSCILLATOR. Instead of a lamp and photocell, two coils are used as shown in Figure 16(b). The coils are closely placed so that their magnetic fields affect each other. Oscillator circuits can be designed to produce any frequency including those for sound, radio, television and so on.

AC COMPONENTS

In the study of dc circuits, the only component used was the resistor. We did, however, also use lamps and switches but these devices are basically also forms of resistance.

In ac circuits, we will encounter five major components. These are indicated in Figure 17. The first component shown is the resistor which is as important in ac as in dc.

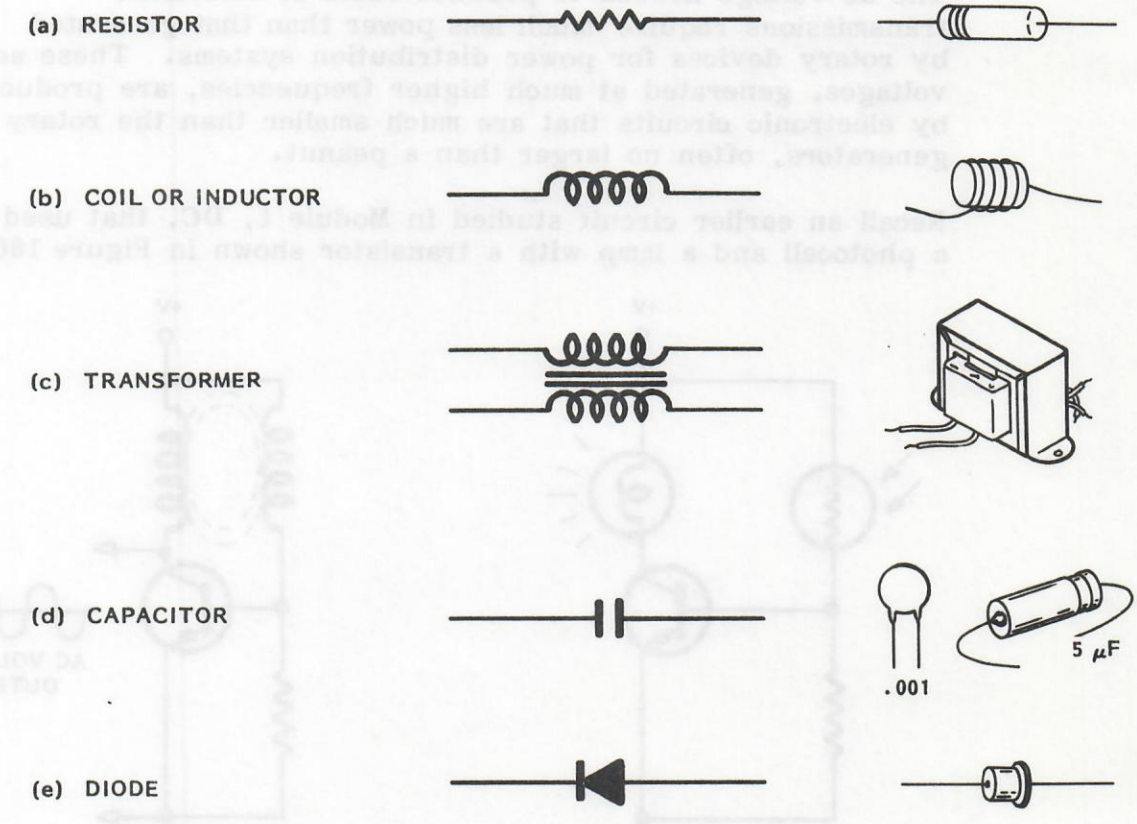


Figure 17 - Components that are used in ac circuits.

THE CAPACITOR AND AC

The resistor, the inductor and the transformer have all been described in previous experiments and information sheets. We will now examine the basic concepts of the capacitor. A capacitor consists of two metal plates separated by an insulator. The insulator may be air as shown in Figure 18.

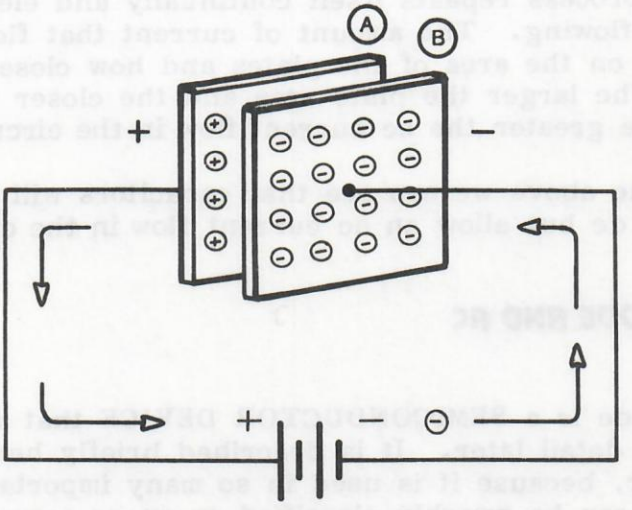


Figure 18 - Electron flow in a capacitor connected to dc.

When the capacitor shown in Figure 18 is first connected to the dc source, electrons flow from the negative terminal of the voltage source and enter plate B. For each electron that enters plate B one electron is forced off plate A by the electric field. Electrons continue to enter plate B and leave A to return to the battery until plate B will accept no more electrons; the capacitor is CHARGED. There is no more current flow after the initial charge and so we say that a capacitor will not pass dc, or it BLOCKS dc.

When a capacitor is connected to an ac source, as shown in Figure 19, its behavior is very different.

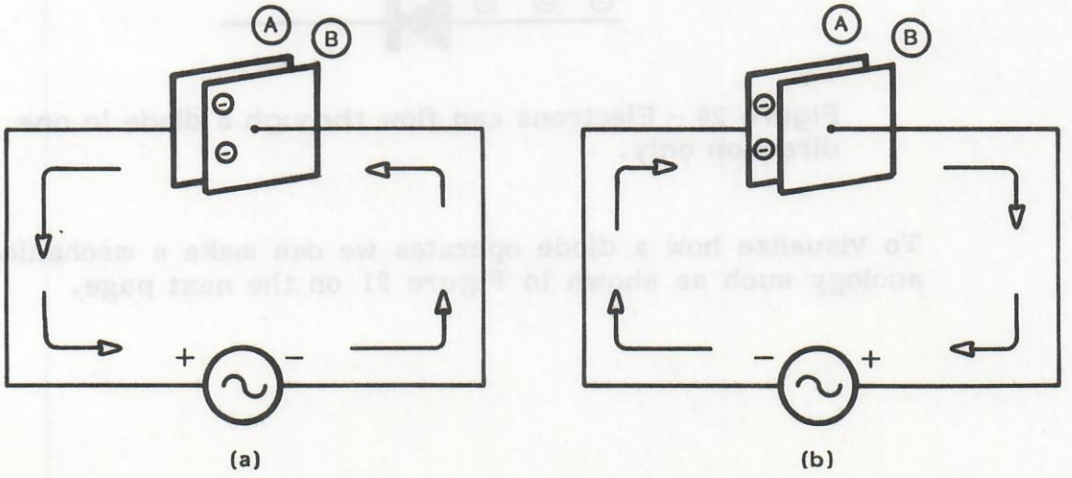


Figure 19 - Electron flow in a capacitor connected to ac.

When the ac polarity is as shown in (a), plate B is charged with electrons, and plate A gives up electrons creating a brief current flow.

Then, as shown in (b) of Figure 19, the ac polarity reverses and electrons rush into plate A and leave plate B. The entire process repeats itself continually and electrons are always flowing. The amount of current that flows will depend on the area of the plates and how close together they are. The larger the plate area and the closer together they are, the greater the ac current flow in the circuit.

From the above we can see that capacitors will block the flow of dc but allow an ac current flow in the circuit.

THE DIODE AND AC

The diode is a SEMICONDUCTOR DEVICE that will be studied in greater detail later. It is described briefly here, however, because it is used in so many important ac circuits that it can be roughly classified as an ac component.

Consider that electrons can flow freely in two directions (ac) in a wire. A diode, however, is a one way valve for electron flow. Electrons can flow through the diode in one direction but not the other as shown in Figure 20.

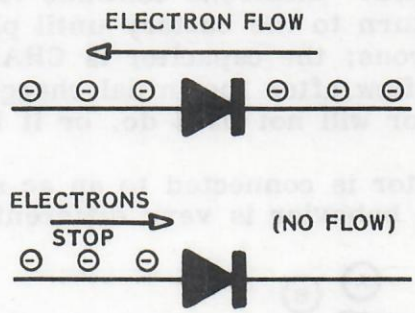
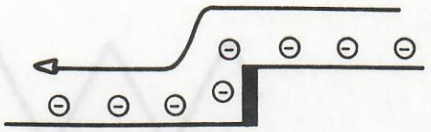


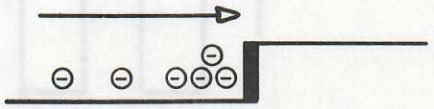
Figure 20 - Electrons can flow through a diode in one direction only.

To visualize how a diode operates we can make a mechanical anology such as shown in Figure 21 on the next page.

(a) DIODE SYMBOL



(b) FORWARD DIODE CURRENT FLOW



(c) REVERSE DIODE CURRENT STOPPED

Figure 21 - Mechanical concept of diode operation.

As shown in (a) of Figures 20 and 21, electrons can flow against the direction of the arrow but not with the direction of the arrow.

If we were to apply an ac voltage to a diode, then current would flow only half the time and only half of the ac voltage would appear at the output end of the diode. This is illustrated below in Figure 22.

Figure 22 - Effect of diode on ac voltages.

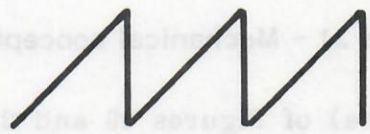
AC WAVESHAPES

Any ac voltages shown thus far have been "smooth" waves that are described as "sinusoidal" waves or simply sine waves. These are discussed thoroughly in later information sheets. Other shapes or ac waveforms are also present in many circuits. Some of these ac waveforms are shown in Figure 23 on the next page.

(a) SINE WAVE

(b) TRIANGLE WAVE

(c) SQUARE WAVE



(d) RAMP WAVE

(k) VOICE WAVEFORM (HELLO)

Figure 23 - Various ac waveshapes.

COMPUTERS

Digital Computers and Microcomputers operate using electrical voltages that are always changing for different information codes. These changing voltages, while ac, are not sinewaves but square waves with sharp "rises and falls." This is illustrated in Figure 24.

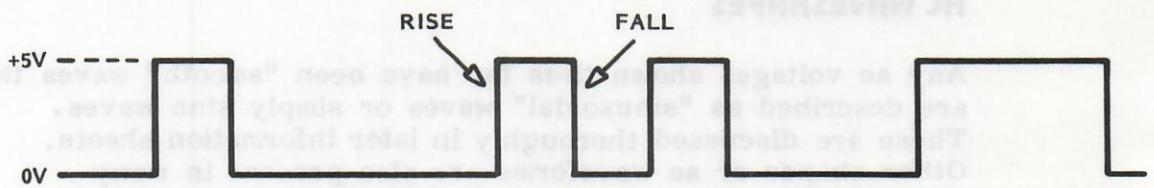


Figure 24 - Typical digital computer AC voltage waveform.

As shown, the waveforms vary between zero and five volts and are called PULSES. The typical computer frequencies are on the order of three million hertz (3 mHz).

SUMMARY

Ac voltages and currents are most important in all areas of electricity and electronics. These areas include power distribution, audio which includes hi-fi and sound systems, radio transmission and reception for both entertainment and commercial communications, television, microwave communications, electronic telephones and computers.

CONCLUSIONS

We have learned from this experiment that:

DC power distribution systems are very inefficient and are no longer used.

Power distribution is accomplished using ac generators because ac voltages can be raised or lowered using transformers.

The higher the voltage applied to the power transmission lines, the lower the current and the lower the I^2R losses

Transformers can raise or lower ac voltages but do not operate on dc.

When ac voltages are connected to a dipole antenna, electromagnetic fields are created.

The electromagnetic fields generated on an antenna break away and are radiated through the air.

An antenna that radiates electromagnetic waves into the air is called a "Transmitting" antenna.

The electromagnetic waves radiated into the air by the antenna is called a "Radio Wave" or "Signal."

The electric and magnetic parts of the electromagnetic waves are at right angles to each other.

To accomplish "Wireless Transmissions" a duplicate of the transmitting antenna is placed in the path of the electromagnetic waves.

An antenna placed in the path of the electromagnetic waves will have a voltage induced into it and thus it is called a "Receiving" antenna.

A microphone converts sound into equivalent electrical energy.

A speaker converts electrical energy into equivalent sound.

All ac voltages have a Frequency which is measured in cycles per second (cps) or in hertz (Hz).

Two cycles of ac are shown below in Figure 25. The wavelength, measured in feet or meters is marked off from peak to peak.

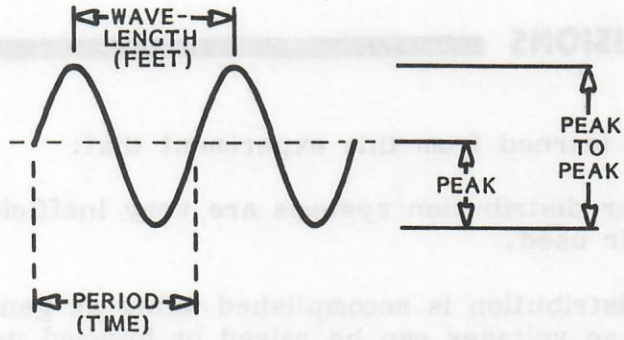


Figure 25

The period is the time required to complete one cycle and is marked off in Figure 25.

The amplitude of the ac wave can be measured as the peak or peak to peak voltage as shown in Figure 25.

The higher the frequency of an ac wave, the shorter its wavelength.

The symbol for wavelength is Lambda, λ.

Ac signals at power line frequencies, 50 or 60 Hz, are generated by rotary machines.

Ac signals at higher frequencies are generated by electronic circuits called oscillators.

Components that are used in ac circuits are inductors, (also called coils), transformers, capacitors and diodes.

A capacitor is formed by two metal plates separated by an insulator.

A capacitor blocks the passage of dc but will permit the flow of ac in the circuit.

The diode will pass a current flow in one direction but not in the reverse direction.

Not all ac voltages have a sine waveshape. Nonsinusoidal waveshapes that are frequently encountered in electronics are ramp or sawtooth voltages, triangular and square waveforms.

Computers also work on ac voltages in the form of strings of pulses called pulse trains.

ASSIGNMENT

Answer the following True-False questions.

1. The letters "ac" represent "alternating current" created by a voltage whose polarity reverses at a constant rate. ____

2. Dc power distribution systems are no longer in use because, while more effective than ac distribution systems, they are more expensive. ____

3. The higher the voltage at which a power system is distributed the lower the I^2R losses on the lines due to the lower current flow. ____

4. In dc distribution systems it is possible to generate output voltages much greater than 120 volts but there is no practical method of lowering the dc to a useable value. ____

5. Ac power systems are used because it is possible to raise the generator output voltage to a very high value for distribution over the power lines with very low losses. ____

6. Transformers are used to step up ac or dc voltages but can only reduce ac back to 120 volts. ____

7. Transformers for use at power line frequencies consist of two windings wound on a soft iron core. ____

8. Ac voltages, when connected to an antenna, generate both an electric and a magnetic field. ____

9. The electromagnetic field generated by an antenna radiates out into the surrounding air. ____

10. Ac voltages have a frequency which is the time required to complete one cycle. ____

11. The amplitude of an ac wave is measured from the negative peak to the positive peak. ____

12. Ac voltages at power line frequencies are generated for distribution on the power lines by oscillator circuits. ____

13. A capacitor blocks the passage of ac but permits dc to flow. _____

14. A diode will pass an electron flow in one direction only. _____

15. Only sine waves are considered to be ac and ramp and square waves are dc. _____

KEY TERMS

1. ALTERNATING CURRENT (ac)

   A flow of electrons in one direction that reaches a maximum value, drops to zero, then reverses direction. The reverse direction current flow rises to a maximum value and drops to zero again.

2. AMPLITUDE

   The magnitude of the variation in an ac voltage or current measured from its zero value.

3. ANTENNA

   A wire or series of wires or metal rods used to transmit or receive electromagnetic radio waves.

4. CAPACITOR

   A device used in ac circuits that consists of two conductors separated by an insulator. The capacitor is capable of storing energy and returning it to the circuit.

5. COIL

   Another name for an inductor which consists of a coil of wire. The coil can store energy in its magnetic field and return the energy to the circuit.

6. DIODE

   A semiconductor device that permits electron flow in one direction only.

7. EARPHONE

   A device, placed over the ear, that converts electrical impulses to equivalent sound. The earphone can also be used as a microphone.

8. ELECTROSTATIC FIELD

   Invisible lines of force that exist between two bodies that are at different electrical potentials.

9. ELECTROMAGNETIC FIELD

   A moving electric field and its associated magnetic field. The two fields are perpendicular to each other.

10. FREQUENCY

The number of recurrences of a cycle in one second, measured in hertz (Hz).

11. INDUCTOR

A component formed from turns of wire (also called a coil). The inductor can store energy in its magnetic field and return the energy to circuit.

12. LAMBDA (λ)

The Greek letter, Lambda (λ), is used to designate wavelength which is measured in meters.

13. MICROPHONE

A device that converts sound energy into an equivalent electrical energy.

14. MODULATION

The process of varying a high frequency radio wave so that it will "carry" intelligence, such as voice or music signals, to distant receiving points.

15. OSCILLATOR

A circuit that converts dc to an ac with a specific frequency.

16. PEAK VOLTAGE

The highest value of an ac voltage that occurs during one alternation of an ac cycle.

17. PEAK-TO-PEAK VOLTAGE

The value of an ac voltage measured from the positive peak to the negative peak.

18. PERIOD

The time, in seconds, required to complete one cycle of an ac wave.

19. RAMP VOLTAGE

A voltage that rises from a low to high value whose rise in value is at a linear rate. Also called a sawtooth waveform because of its resemblance to the teeth of a saw blade.

20. SOUND SYSTEM

A system that consists of a microphone to change sound to equivalent electrical energy, an amplifier to strengthen the electrical energy and a speaker to convert the strengthened electrical energy back to sound.

21. SPEAKER

A device used to convert electrical signals into equivalent sound energy.

22. SQUARE WAVE

A voltage that rises straight up from the low to high value, remains at the high value for a given time, and then drops straight down, back to the low value. The voltage remains at the low value for a given time and then the cycle repeats.

23. STEP-DOWN TRANSFORMER

A transformer that accepts a high ac input voltage and produces a lower ac output voltage.

24. STEP-UP TRANSFORMER

A transformer that accepts a low ac input voltage and produces a higher ac output voltage.

25. TRANSFORMER

Two or more windings on a common iron core which can transfer electrical energy from one winding to another by magnetic coupling.

26. WAVELENGTH

The wavelength of a cycle of ac is the dimension occupied by a single cycle of the ac. It is the same dimension as the period, but measured in meters.

27. WIRELESS

A term used in the 1900's for radio transmissions and still used by the British.

Observing Effect of AC Voltages 1

OBJECTIVES

When you finish this experiment, you will be able to:

1. Identify the two ac power sources on the Ed-Lab trainer.
2. Describe the ac sources as they affect a lamp, loudseaker and dc meter movement.
3. Describe lamp flicker at low ac frequencies.
4. Adjust the frequency of the Function Generator over the 1 Hz to 100 kHz range.
5. Determine the low and high limits of your hearing.
6. Identify a 60 Hz tone.

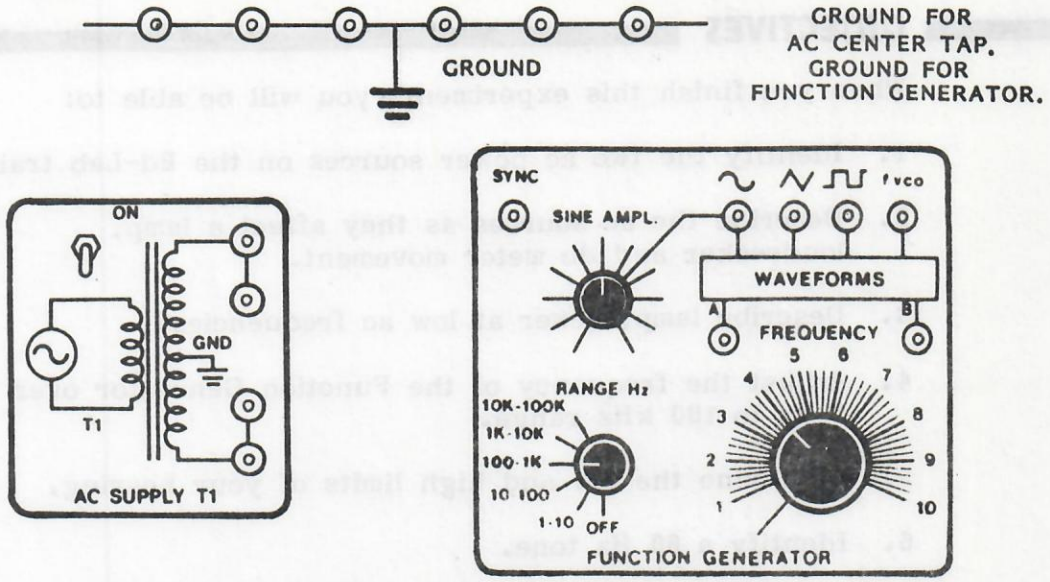
DESCRIPTION

There are two sources of AC VOLTAGE available on the Ed-Lab trainer and they correspond to the two general areas of application described earlier. These are:

1. Ac voltage at the power line frequency (60 Hz).
2. Ac voltage at Audio and low Radio frequencies (up to 100 kHz).

These two ac voltage sources are indicated in Figure 1. The 60 Hertz source is obtained from the power line through a step-down transformer although the symbol in Figure 1(a) shows a step-up transformer. (As a rule, step-up and step-down ratios are not accurately shown by the number of turns drawn on each transformer winding.) The Ed-Lab 651 transformer reduces the 120 volt power line to 10 volts from each end of the secondary to ground or a total of 20 volts across the full secondary. As shown in Figure 1(a), the center tap of the secondary is connected to ground, but the ground connection must be made at a row of ground jacks at the top of the panel.

The Ed-Lab 651 FUNCTION GENERATOR and AC METER are mounted on the trainer panel. In the field, these two instruments are separate devices, each in its own cabinet. When using the Ed-Lab 650, the earlier version of the Ed-Lab 651, you must use these two external instruments and, for some experiments, the test results might change slightly. It is also necessary, as part of a complete training program, to be familiar with the use of external test equipment. This experience with instruments is separately provided.



(a) 60 Hz POWER SOURCE (b) SIGNAL SOURCE 1Hz TO 100 kHz

Figure 1 - Ac voltage sources on the Ed-Lab trainer.

The FUNCTION GENERATOR, shown in Figure 1(b), provides three output waveforms:

1. Sine Wave (rounded)
2. Triangular
3. Square

The Function Generator frequency is variable from 1 Hertz to 100,000 Hertz in 5 range steps with a Frequency knob. If the Range knob is set at 100 - 1 K and the Frequency knob is set at 4, the output frequency is 400 Hertz. This is because the Range knob specifies a frequency between 100 and 1000 Hertz and so the 4 setting of the Frequency dial must represent 400.

The output waveforms are sine, triangle and square, each available from separate jacks. Only the sine wave amplitude is adjustable using the knob marked SINE AMPL.

In this experiment you will use the variable frequency Function Generator to produce ac voltages of different frequencies and observe their effect on three devices:

1. LAMP (visible light energy)
2. METER (visible mechanical movement)
3. SPEAKER (air motion and sound)

PROCEDURE

1. Wire the TRIANGLE waveshape output to drive the lamp, LAMP 1, as shown in Figure 2.

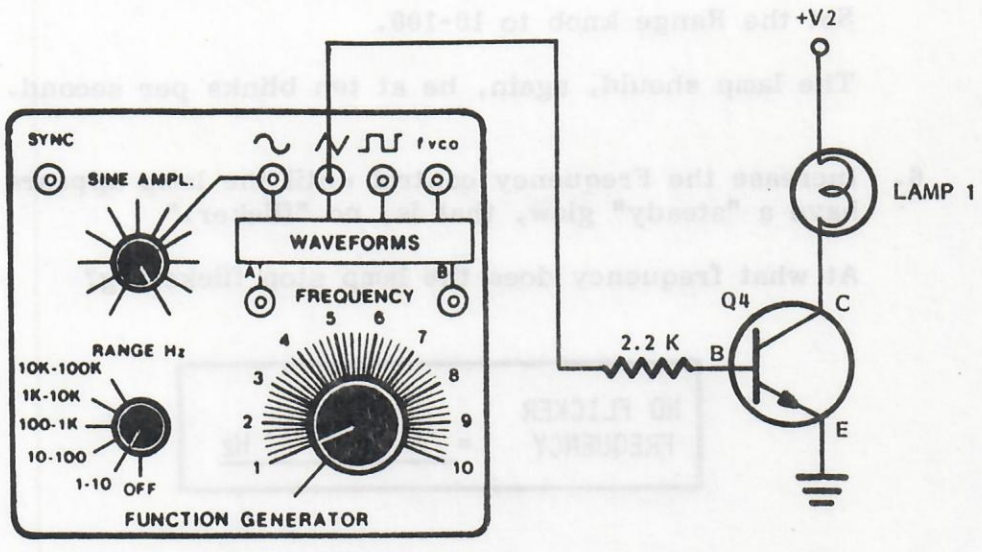


Figure 2 - Ac voltage and lamp EXPERIMENT.

Transistor Q4 is used to provide enough current to light Lamp 1.

1.1 LAMP INDICATOR

2. Set the Function Generator controls as shown in Figure 2 to provide a 1 Hz output.

   a. RANGE Hz 1-10
   b. FREQUENCY 1
   c. SINE AMPL. Maximum clockwise

3. Observe the operation of the lamp and describe it below.

   The lamp should be blinking on and off at a one hertz rate or one blink per second.

4. Rotate the Frequency knob on the Function Generator to 10.

   Can you still see the lamp blinking? _____

   How fast is it blinking? _____

5. Rotate the Frequency control back to 1.

   Set the Range knob to 10-100.

   The lamp should, again, be at ten blinks per second.

6. Increase the Frequency control until the lamp appears to have a "steady" glow, that is, no "flicker."

   At what frequency does the lamp stop flickering?

NO FLICKER FREQUENCY = _____ Hz

7. The power line frequency is 60 Hz. Will a lamp operated from the 60 Hz power line produce flicker? _____

   _____

   In Europe, the power line frequency is 50 Hz. Will this cause flicker on a lamp operated from the 50 Hz line? Why?

   _____

   _____

   _____

   If a power system is designed to distribute a 20 Hz ac voltage, do you think any problems would be encountered and why?

   _____

   _____

   _____

1.2 METER

8. Connect the meter to the output of the Function Generator as shown in Figure 3, but leave the existing wiring.

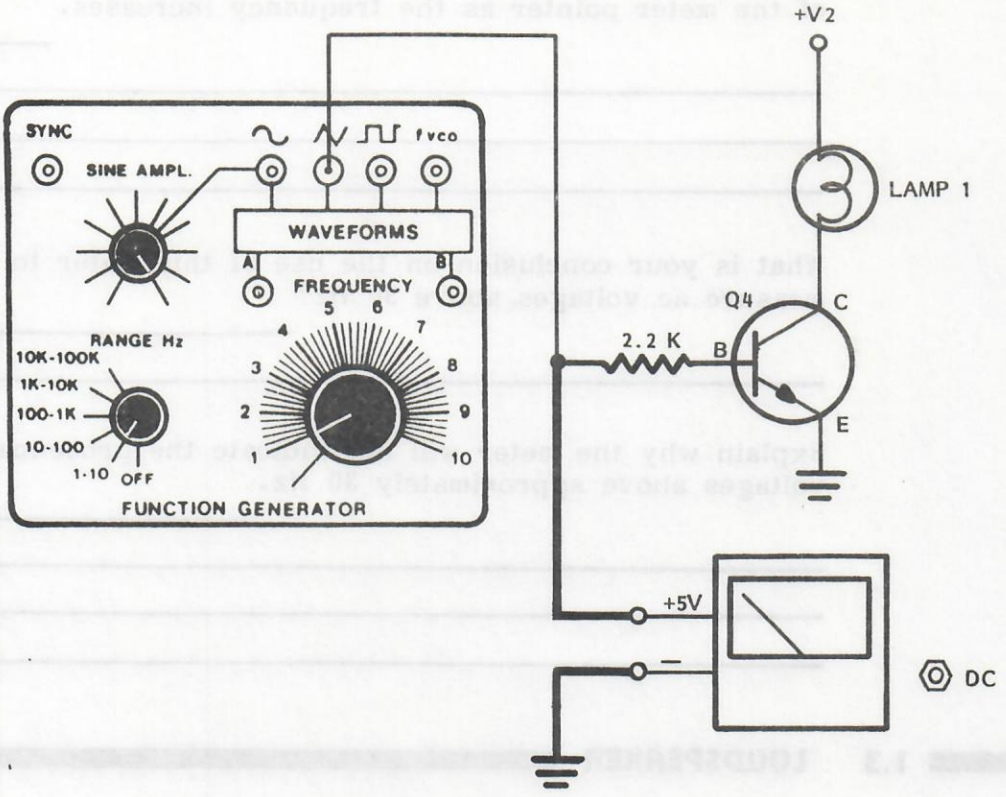


Figure 3 - Added meter circuitry is drawn in bold lines; EXPERIMENT.

9. Set the Function Generator to 1 Hz and observe the meter. Describe what is occuring.

Could a meter of this type be useful to observe a frequency of 1 Hz? Why?

10. Increase the frequency slowly from 1 Hz to 10 Hz. Observe that the meter pointer vibrates and is no longer a useable measuring device.

11. Increase the frequency to 60 Hz. Describe the behavior of the meter pointer as the frequency increases.

What is your conclusion on the use of this meter to measure ac voltages above 30 Hz?

Explain why the meter will not indicate the presence of ac voltages above approximately 30 Hz.

1.3 LOUDSPEAKER

12. Disconnect the Lamp and meter from the output of the Function Generator and connect the speaker through a 100 ohm resistor as shown in Figure 4.

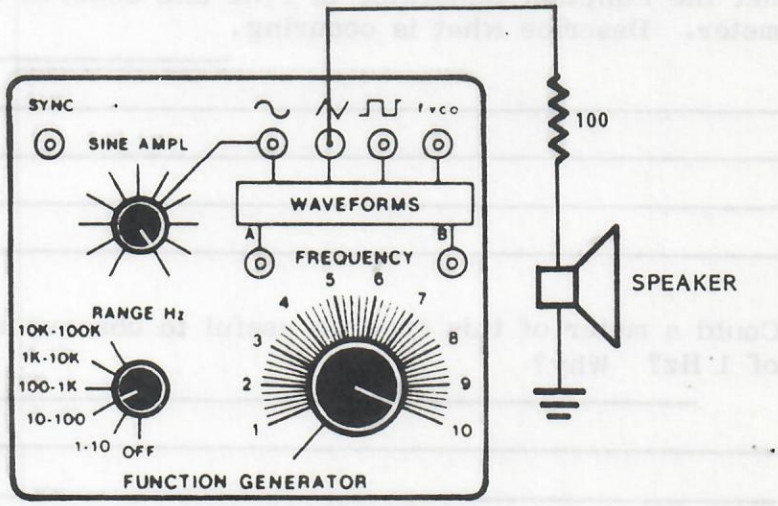


Figure 4 - Speaker connected to the Function Generator output; EXPERIMENT.

The purpose of the 100 ohm resistor is to limit the ac current drained from the Function Generator and to keep the sound level down.

13. Set the Function Generator frequency to 100 Hz (Range: 10-100; Frequency: 10).

Describe the sound you hear from the speaker at 100 Hz.

_____

_____

14. Gradually reduce the frequency to 60 Hz.

Do you still hear any sound from the speaker?

_____

This is the sound of HUM that you often hear from the speaker of a radio that is operated from the 60 Hz power line.

15. Slowly reduce the frequency further until you do not hear any tone.

Now increase the frequency slowly until you hear a tone.

This is the lowest frequency heard from a combination of the reproduction quality of the speaker and the hearing capability of your ear.

Record the lowest frequency you can hear.

LOWEST SOUND FREQUENCY = _____ Hz

16. Increase the Function Generator to the 1 K to 10 K Range. Vary the frequency over the full range.

What is the highest frequency you can hear in this range?

_____

If you cannot hear 10 kHz, record the highest frequency below 10 kHz, that you can hear, in the box on the next page, and skip step 17. If you can hear up to 10 kHz, increase the Function Generator setting to the 10 K - 100 K position.

17. Increase the frequency from 10 kHz upward. What is the highest frequency you can hear?

HIGHEST SOUND FREQUENCY = _____ kHz

The audible range of frequencies is from 20 Hz to 20 kHz but the highest frequency heard will vary greatly from person to person.

1.4 SQUARE WAVE

18. Remove the plug from the Triangle wave jack and insert it into the Square Wave jack as shown in Figure 5 below.

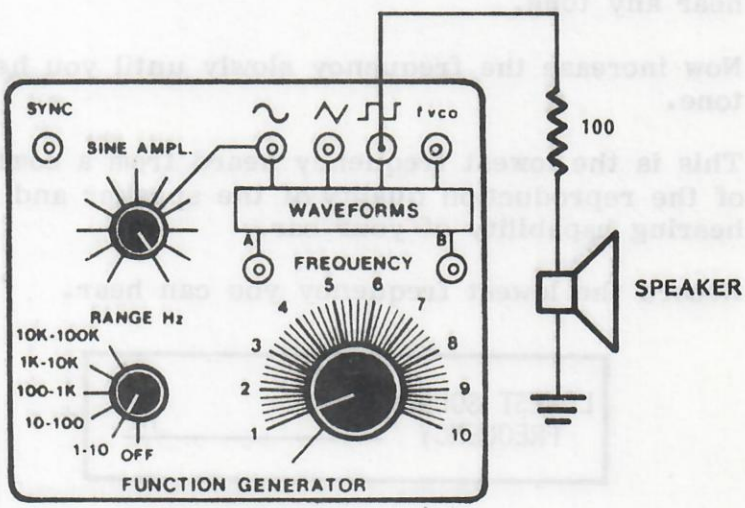


Figure 5 - Speaker driven by the square wave; EXPERIMENT.

19. Reduce the frequency to 1 Hertz.

In step 15 you were unable to hear any response from the speaker between 1 and 10 Hz on the Triangle output.

Vary the generator frequency between 1 and 10 Hz.

Can you hear the sound now? _____

The square wave provides rapid changes in voltage from plus to minus and back to plus again. This causes abrupt and rapid changes in the speaker cone displacement. These changes are really, in effect, higher frequencies. You do hear the higher frequency components of the 1 Hz tone but do not hear the 1 Hz signal itself. This concept will be expanded upon later.

1.5 60 HERTZ POWER SIGNAL

20. Remove the speaker plug from the Square Wave jack on the Function Generator and connect it to the 60 Hz power source as shown in Figure 6.

    Also, reconnect the meter and Lamp 1 as shown in Figure 6.

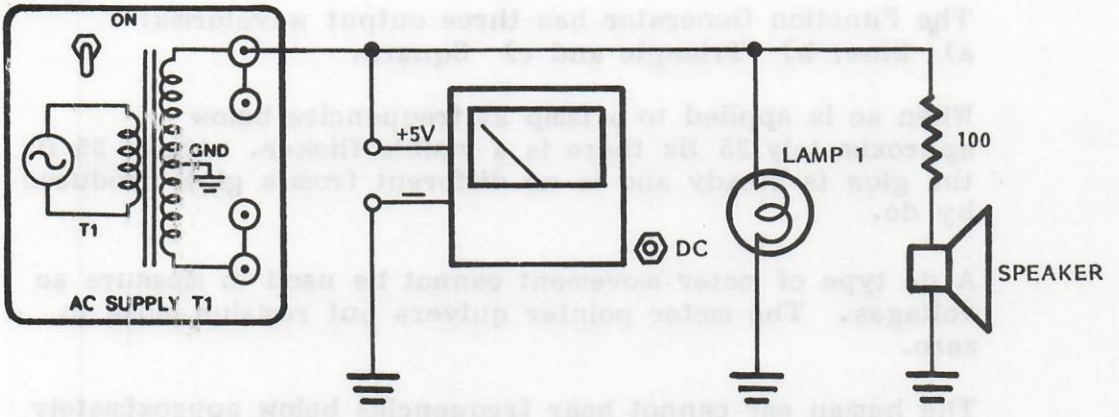


Figure 6 - Speaker, Lamp 1 and dc meter connected to the 60 Hz ac power source; EXPERIMENT.

21. Does the lamp blink? _____

22. What does the voltmeter read? _____

23. What type of sound do you hear? _____

_____

CONCLUSIONS

We have learned from this experiment that:

The Ed-Lab 651 trainer has two sources of ac, the 60 Hz power line and the Function Generator.

The Function Generator can provide any frequency between 1 Hz and 100 kHz in five ranges.

The Function Generator has three output waveforms: a) Sine; b) Triangle and c) Square.

When ac is applied to a lamp at frequencies below approximately 35 Hz there is a visible flicker. Above 35 Hz the glow is steady and is no different from a glow produced by dc.

A dc type of meter movement cannot be used to measure ac voltages. The meter pointer quivers but remains close to zero.

The human ear cannot hear frequencies below approximately 20 Hz.

The upper frequency limit of hearing varies from person to person and can range from as low as 5 kHz up to 20 kHz or more.

ASSIGNMENT

Answer the following True-False questions.

1. When the frequency of an ac voltage applied to a lamp is below approximately 35 Hz there will be visible flicker in the light output. _____

2. A lamp connected to a 50 Hz power source will produce a visible flicker in its light output but will not when connected to a 60 Hz source. _____

3. A dc meter can be used to measure ac if the scale reading is multiplied by the correct factor to allow for the time required by the pointer to move up scale. _____

4. A loudspeaker, when connected to a source of ac within the audible range, will convert that ac to sound. _____

5. The response of the average person to sound is from 20 Hz to 200 kHz. _____

KEY TERMS

1. FLICKER

   A light source that is unsteady, wavers or flutters.

2. FUNCTION GENERATOR

   A circuit or instrument that generates ac voltages of different waveshapes and whose frequency can be varied typically from 1 Hz to 100,000 Hz.

3. LOUDSPEAKER

   Also called a speaker, it is a device used to convert electrical signals into equivalent sound energy.

4. TRANSISTOR

   An electronic device that is used to strengthen (amplify) a current.

Alternating Current and Voltage

INFO SHEET 2

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Describe what is meant by an alternating voltage.
2. Explain how an alternating voltage is generated.
3. Define what is meant by a sine wave.
4. Draw a sine wave and calibrate the time axis in degrees.
5. Calculate the instantaneous voltage at any point in the sine wave.
6. Define what is meant by an alternation and a cycle of a sine wave.
7. Define what is meant by the period and frequency of a sine wave.
8. Convert the period of a sine wave to frequency and frequency to period.
9. Define the meaning of peak, peak-to-peak, rms and average values of a sine wave.
10. Convert sine wave measurements from peak to rms, to peak-to-peak and to average.

DISCUSSION

In all the experiments performed up to now, the voltage source used had one positive and one negative terminal and the current always flowed in one direction, from minus to plus. Current that flows in one direction only is called "Direct Current," is abbreviated "dc" and is illustrated in Figure 1.

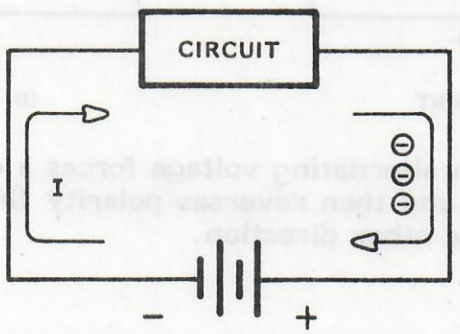


Figure 1 - Current flows in one direction only when a circuit is powered by a dc source.

DC POWER DISTRIBUTION SYSTEMS

The early electrical power distribution systems for home and industry used dc. The direct current system of power distribution has some serious disadvantages. These were an inability to easily raise and lower the value of the generated voltage resulting in large power losses when distributing power.

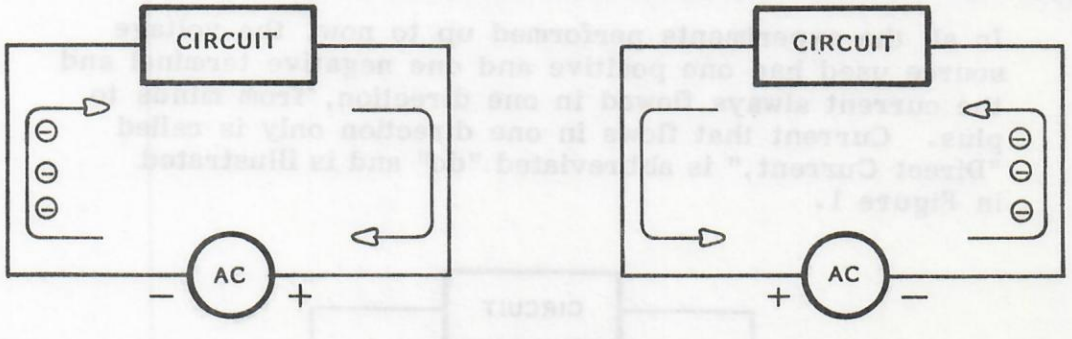
ALTERNATING CURRENT SYSTEMS

As more homes were added to the electrical system and more electrical appliances using motors were invented, the dc system became inadequate and the answer to the problem was to increase the voltage on the power distribution lines to reduce the current and the lost power. The results, however, would be an increased shock hazard with outlet voltages of 240 to 500 volts or more.

The answer to the problem was the development of "ALTERNATING CURRENT." The use of alternating current, abbreviated "ac," allows the generator output voltage to be increased or decreased through the use of transformers.

ALTERNATING VOLTAGE

The generator that develops ac, forces a current flow through a circuit in one direction and then reverses its polarity to force a current flow in the opposite direction as shown in Figure 2.



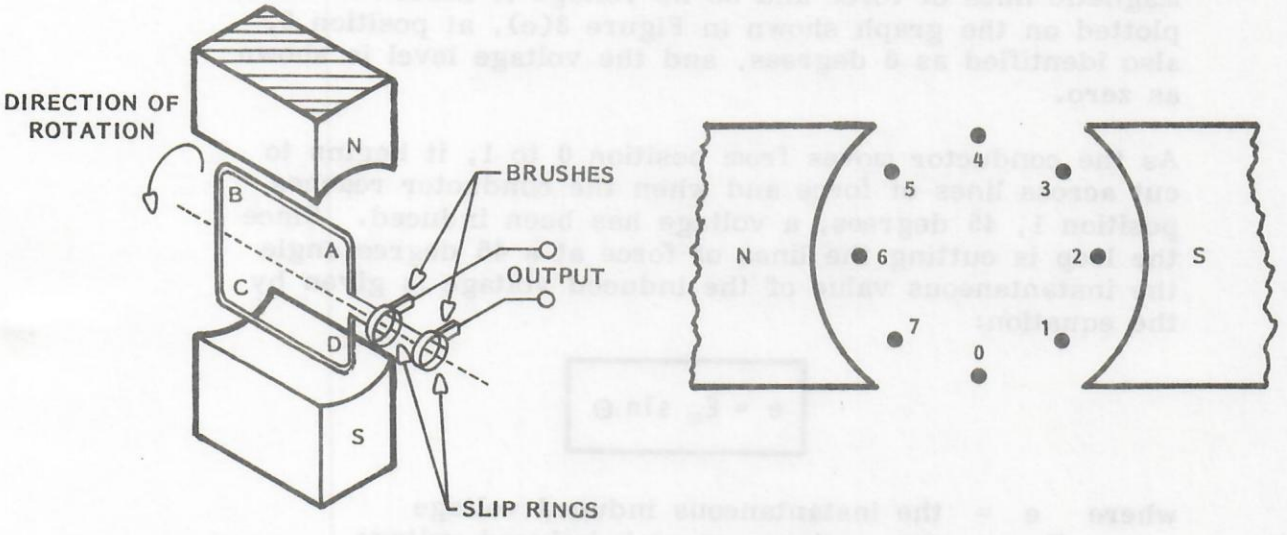
(a) FIRST MOMENT (b) A MOMENT LATER

Figure 2 - An alternating voltage forces a current in one direction (a) and then reverses polarity (b) to force a current in the other direction.

AC GENERATORS

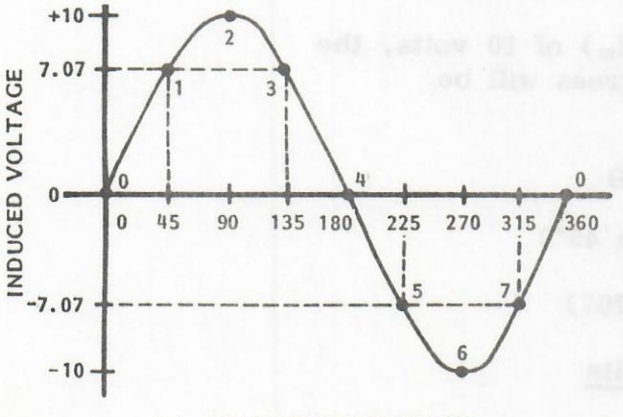
Information Sheet 3, Induction, Unit F1, explained how a voltage is induced in a wire as it passes through a magnetic field. It was noted that the induced voltage was determined by the speed of the wire movement and the number of lines of force being cut. Also explained was that the polarity of the induced voltage is dependent upon the direction of the wire movement and the magnetic polarity.

Consider a generator armature formed from a single loop of wire and placed in a magnetic field as shown in Figure 3(a). The loop is rotated by the prime mover, a steam or water turbine as an example. The voltage developed by the armature as it rotates in the field is connected to SLIP RINGS which rotate with the armature. Brushes are placed in



(a) AC GENERATOR CONSTRUCTION

(b) GENERATOR ARMATURE POSITIONS



(c) AC OUTPUT VOLTAGE

(d) AC GENERATOR SYMBOL

Figure 3(a) - Basic construction of an ac generator. (b) - Plot of loop positions in the magnetic field every 45 degrees. (c) - Plot of resultant output voltage induced in the armature loop. (d) - Ac generator symbol.

contact with the slip rings to make electrical connection to the rotating rings. The slip rings in the ac generator are similar to the commutator described in Information Sheet 4, F1.

As the loop in Figure 3(a) is rotated, sections AB and CD of the loop cut across the magnetic lines of force. If the loop rotation is divided into 8 segments of 45 degrees each (360/8 = 45 degrees), as shown in Figure 3(b), it is possible to determine the output voltage for one revolution of the loop (360 degrees).

A voltage will be induced into a wire that cuts across a magnetic field but no voltage will be induced in a wire that moves parallel to the magnetic field. When wire AB is in position 0 of Figure 3(b), it is moving parallel with the magnetic lines of force and so no voltage is induced. This is plotted on the graph shown in Figure 3(c), at position 0, also identified as 0 degrees, and the voltage level is shown as zero.

As the conductor moves from position 0 to 1, it begins to cut across lines of force and when the conductor reaches position 1, 45 degrees, a voltage has been induced. Since the loop is cutting the lines of force at a 45 degree angle the instantaneous value of the induced voltage is given by the equation:

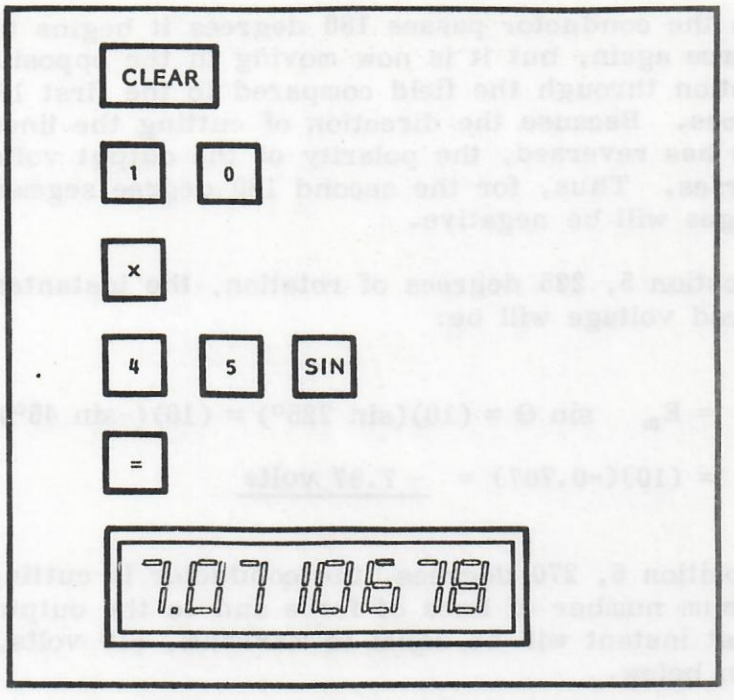
$$e = E_m \sin \Theta$$

where e = the instantaneous induced voltage
E_m = the maximum or peak induced voltage
Θ = the angle of the loop rotation

Thus, for a maximum output (E_m) of 10 volts, the instantaneous voltage at 45 degrees will be

$$e_{45°} = E_m \sin \Theta$$
$$= (10)(\sin 45°)$$
$$= (10)(0.707)$$
$$e_{45°} = \underline{7.07 \text{ volts}}$$

To simplify the above calculations and avoid the use of trigonometric tables, a scientific calculator with trigonometric capability can be used as follows:



The answer rounds off to 7.07 volts.

When the rotating armature moves another 45 degrees to 90 degrees, time 2 in Figure 3(b) and (c), it is cutting the lines of force at right angles and the instantaneous voltage is at maximum as the next calculation shows.

$$e_{90°} = E_m \cdot \sin \Theta = (10)(\sin 90°) = (10)(1) = \underline{10 \text{ volts}}$$

When the rotating conductor moves another 45 degrees to 135 degrees at time 3, it is again cutting the lines of force at a 45 degree angle and so the instantaneous voltage drops. The induced voltage will be the same as position 1, 7.07 volts.

At 180 degrees, time 4, the conductor is again moving parallel with the lines of force. No voltage is induced and so the instantaneous voltage has dropped to zero as shown in Figure 3(c). This can be shown mathematically as:

$$e_{180°} = E_m \cdot \sin \Theta = (10)(\sin 180°) = (10)(0) = \underline{0 \text{ volts}}$$

For the first 180 degrees of the rotation, from time 0 to 4, the output voltage increased from 0 volts to a maximum of 10 volts and returned to 0 volts.

When the conductor passes 180 degrees it begins to cut lines of force again, but it is now moving in the opposite direction through the field compared to the first 180 degrees. Because the direction of cutting the lines of force has reversed, the polarity of the output voltage also reverses. Thus, for the second 180 degree segment all voltages will be negative.

At postion 5, 225 degrees of rotation, the instantaneous induced voltage will be:

$$e_{225°} = E_m \quad \sin \Theta = (10)(\sin 225°) = (10)(-\sin 45°)$$

$$e_{225°} = (10)(-0.707) = \underline{-7.07 \text{ volts}}$$

At position 6, 270 degrees, the conductor is cutting the maximum number of lines of force and so the output voltage at that instant will be equal to maximum, -10 volts, as shown below.

$$e_{270°} = E_m \quad \sin \Theta = (10)(\sin 270°) = (10)(-\sin 90°)$$

$$e_{270°} = (10)(-1) = \underline{-10 \text{ volts}}$$

At position 7, 315 degrees, the induced voltage will be

$$e_{315°} = E_m \quad \sin \Theta = (10)(\sin 315°) = (10)(-\sin 45°)$$

$$e_{315°} = (10)(-0.707) = \underline{-7.07 \text{ volts}}$$

At position 8, 360 degrees, the conductor is again travelling parallel to the lines of force and the induced voltage is zero as shown below.

$$e_{360°} = E_m \quad \sin \Theta = (10)(\sin 360°) = (10)(\sin 0°)$$

$$e_{360°} = (10)(0) = \underline{0 \text{ volts}}$$

It can be seen from Figure 3(c) that for the second 180 degrees of rotation (180°to 360°)from time 4 back to time 0, the output voltage increased from 0 volts to a maximum of -10 volts and returned to 0 volts.

SINE WAVE MEASUREMENTS

After the conductor completes one rotation in the magnetic field, 360 degrees, an ac voltage, shown in Figure 3(c) and again in Figure 4, is developed. The output waveshape is called a SINE WAVE because when generating the full cycle, the instantaneous voltage at any angle is equal to the maximum voltage multiplied by the SINE of the angle through which the conductor is moving.

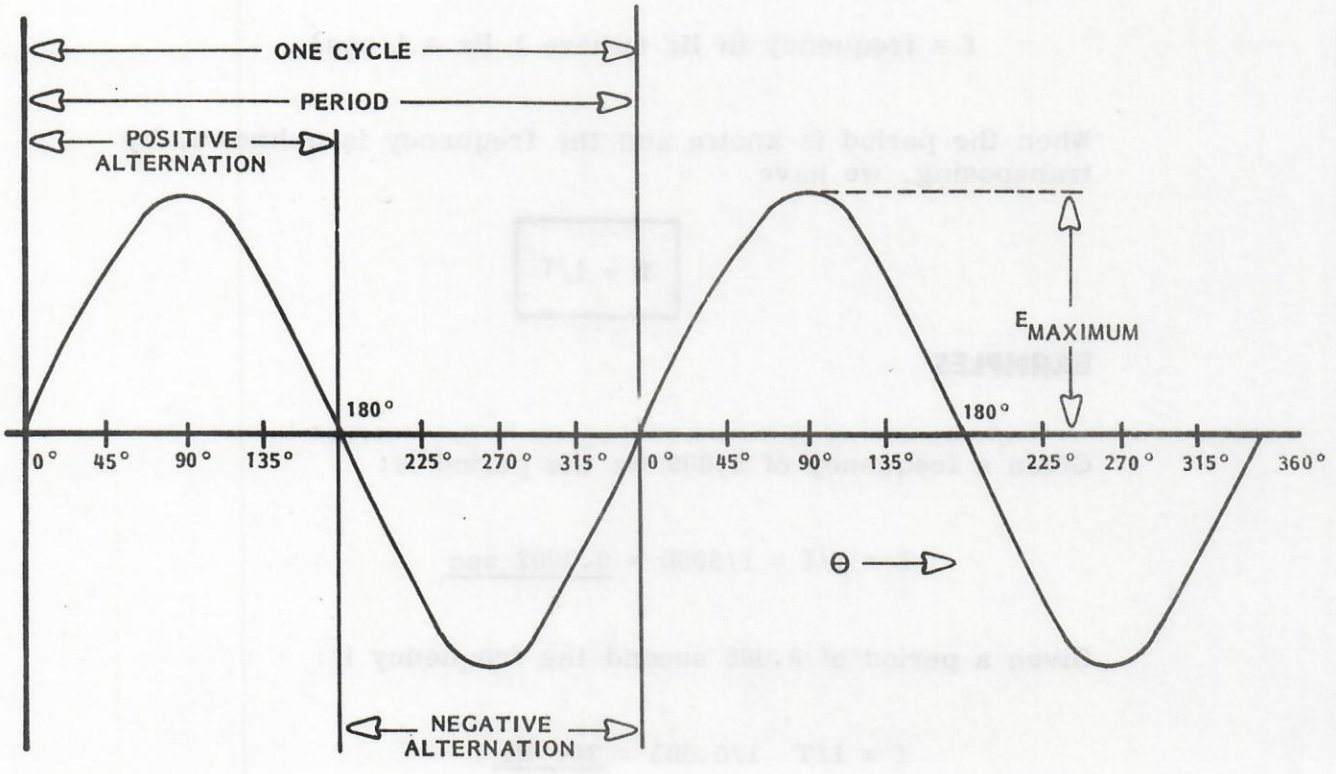


Figure 4 - Two cycles of an ac sine wave voltage.

As shown in Figure 4, the first 180 degrees of rotation creates the positive ALTERNATION and the second 180 degrees creates the negative alternation. Both the positive and negative alternations, combined, form one CYCLE. The waveform then continues.

FREQUENCY

If the loop in Figure 3(a) takes one second to complete a rotation, one cycle of voltage is generated in one second. This represents a FREQUENCY of 1 cycle per second (1 cps) or 1 hertz (abbreviated as 1 Hz). If the speed of rotation of the loop is increased to 1000 revolutions per second, the frequency would be 1000 Hz.

PERIOD

The time required to complete one cycle of a waveform is called the PERIOD and is shown in Figure 4. The period of a cycle is inversely proportional to its frequency. Thus, the higher the frequency, the shorter the period. Expressed mathematically, we have

$$T = 1/f$$

where T = period in seconds

f = frequency in Hz (where 1 Hz = 1 cps)

When the period is known and the frequency is unknown, by transposing, we have

$$f = 1/T$$

EXAMPLES

Given a frequency of 5,000 Hz the period is:

$$T = 1/f = 1/5000 = \underline{0.0002 \text{ sec}}$$

Given a period of 0.005 second the frequency is:

$$f = 1/T \quad 1/0.005 = \underline{200 \text{ Hz}}$$

FREQUENCY UNITS AND RANGES

As noted earlier, the unit of frequency is the hertz. Dc is considered to be zero hertz and the ac power lines are usually all 60 hertz. There are, however, sources of ac from below 60 hertz up to many millions of hertz. To simplify the presentation of higher frequencies we have the most often used "powers of ten" listed in Table 1. Note that only Engineering Notation (powers of 10 at 10^3, 10^6, or 10^9 etc.), is used.

1 Hz	=	1 Hz	
1,000 Hz	=	1 kHz	(10^3 Hz) (kilo)
1,000,000 Hz	=	1 mHz	(10^6 Hz) (mega)
1,000,000,000 Hz	=	1 gHz	(10^9 Hz) (giga)

TABLE 1 - Most often used prefixes for frequency.

Because the useable frequency range or spectrum is so large, it has been divided into blocks or ranges by the Federal Communications Commission (FCC) and these ranges are listed below in Table 2.

FREQUENCIES	RANGE	
0 to 30 kHz	Very Low Frequencies	(vlf)
30 to 300 kHz	Low Frequencies	(lf)
300 to 3,000 kHz	Medium Frequencies	(mf)
3,000 to 30,000 kHz	High Frequencies	(hf)
30,000 kHz to 300 mHz	Very High Frequencies	(vhf)
300 to 3,000 mHz	Ultra High Frequencies	(uhf)
3,000 to 30,000 mHz	Super High Frequencies	(shf)
30,000 mHz to 300 gHz	Extremely High Frequencies	(ehf)

TABLE 2 - Frequency range designation as established by the Federal Communications Commission (FCC).

A listing of commonly used applications of frequencies are given below in Table 3.

HOME & INDUSTRY POWER	50 Hz and 60 Hz
AIRCRAFT POWER	400 Hz
SOUND	20 Hz to 20 kHz
AM BROADCAST BAND	535 kHz to 1605 kHz
FM BROADCAST BAND	88 mHz to 108 mHz
TV VHF BAND	54 mHz to 88 mHz and 174 mHz to 216 mHz
TV UHF BAND	470 mHz to 890 mHz
SATELLITE COMMUNICATIONS	4 gHz to 20 gHz typical
LIGHT SPECTRUM	390,000 gHz to 770,000 gHz

TABLE 3 - Listing of frequencies used for various services.

SINE WAVE VOLTAGE MEASUREMENT

Ac voltages, unlike dc voltages, are constantly changing in value and for this reason can be measured in several different ways. One method of measurement is the value of the maximum positive or negative alternation. This is called the PEAK VOLTAGE and is shown in Figure 5. Since the positive and negative alternations of a sine wave are identical except for polarity, the negative peak voltage is equal to the positive peak voltage.

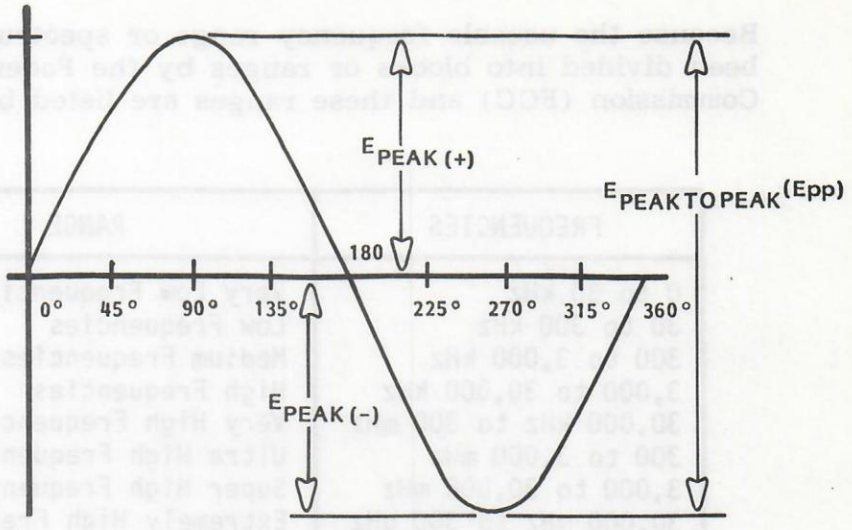


Figure 5 - Peak and peak-to-peak voltage measurements.

PEAK TO PEAK

A second method of indicating the amplitude of a sine wave is the total of both peak voltages. This value of voltage is called PEAK-TO-PEAK, abbreviated p-p, and is also shown in Figure 5. Since the positive and negative peaks are equal, it can be stated that

$$E_{pp} = 2\ E_p$$

EFFECTIVE OR RMS VOLTAGE

One effect of a current flow through a resistance is the production of heat whether it is alternating or direct current. To determine the EFFECTIVENESS of an ac voltage, the heat it develops is compared to the heat or power developed by a dc voltage. If, in a dc circuit, 1 ampere flows, a certain amount of heat will be developed (I^2R). An ac wave (Figure 5) with a peak current of 1A will not develop as much heat as the dc because the ac current is less than 1A most of the time. To determine the EFFECTIVE power value of the ac current we would add the instantaneous voltages for each degree from 0 to 90, square each voltage (to correspond to the power given by I^2R or V^2/R), add them together and divide by 90 to obtain the average or MEAN squared voltage or current. The SQUARE ROOT of this MEAN will then be the EFFECTIVE value or the ROOT MEAN SQUARE value or RMS (written as rms). The calculations of the rms value for a peak of 1A is shown in Table 4. The computations are performed every 10 degrees rather than every 1 degree to make a shorter table which results in a slight error in the answer.

ANGLE	SINE θ	SINE θ^2
0	0.000	0.0000
10	0.174	0.0301
20	0.342	0.1169
30	0.500	0.2500
40	0.643	0.4134
50	0.766	0.5868
60	0.866	0.7500
70	0.940	0.8836
80	0.985	0.9702
90	1.000	1.0000
TOTALS	6.216	5.0010
(÷10) AVERAGE OR MEAN	0.6216	0.5001
SQUARE ROOT OF THE MEAN (rms) SINE θ^2	$\sqrt{0.5001}$ =	0.707

TABLE 4 - Derivation of rms = 0.707 x Peak.

From Table 4 it is possible to see that if the peak current flow for one alternation is 1 amp then the EFFECTIVE value will be 1A times 0.707 or 0.707A. This means that 1A peak ac is the equivalent of 0.707A dc. Expressed mathematically we have:

$$I_{rms} = 0.707 \times I_{peak}$$
$$\text{or } E_{rms} = 0.707 \times V_{peak}$$

Given a peak voltage of 170 volts, the effective value is determined by

$$E_{rms} = (0.707)(E_{Peak})$$
$$= (0.707)(170)$$
$$E_{rms} = 120 \text{ volts}$$

To determine the peak voltage when the rms is known, the formula can be transposed as shown below.

$$E_{rms} = (0.707)(E_{peak})$$

$$E_{peak} = \frac{E_{rms}}{0.707}$$

Since the reciprocal of 0.707 equals 1.414, the formula is most often presented as

$$E_{peak} = (E_{rms}) (1.414)$$

Thus, the ac power line sine wave with an rms value of 120 volts will have a peak value of

$$E_{peak} = (E_{rms}) (1.414)$$

$$= (120) (1.414)$$

AC POWER LINE

$$E_{peak} = 170 \text{ V}$$

It is important to note that the effective or rms value of current or voltage is usually written without any subscripts. Unless otherwise noted, all ac measurements are written in effective values. Thus, when we say that the power outlets in the home or shop provide 120 volts, it means 120 volts rms.

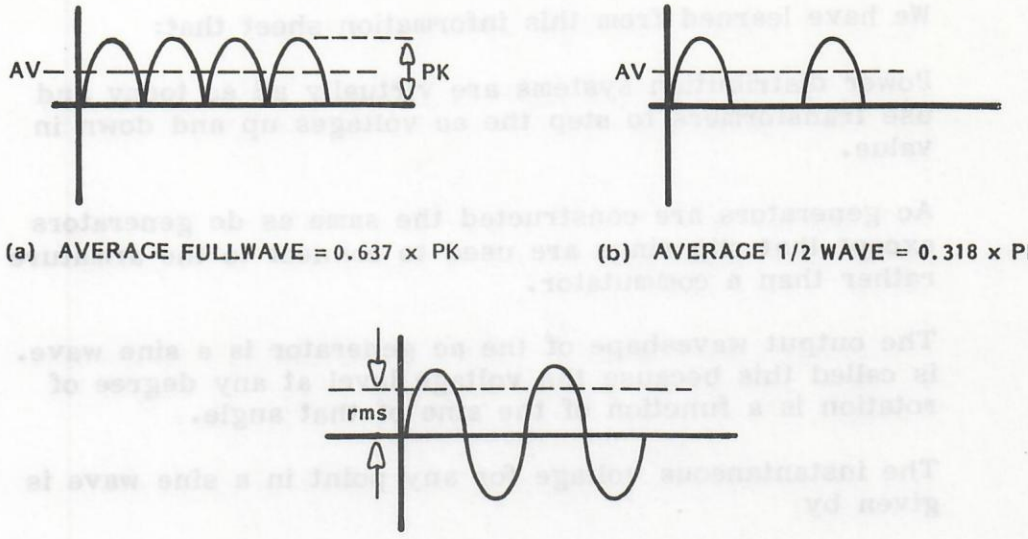
AVERAGE VALUE

If all the instantaneous values of the positive alternation are added to the instantaneous values of the negative alternation, the average of these values will be ZERO volts or amperes. The reason for this is that the two adjacent half cycles are of opposite polarity and equal in value and so cancel each other. Thus, it can be said that the average value of an entire cycle is zero.

If we think only in terms of one alternation (either the positive or negative) with a peak of 1 volt, the instantaneous voltages taken every 10 degrees, as in Table 4, resulted in a total average of 0.6216 volts. Taken at every degree, the instantaneous voltages will total to a more accurate value of 0.636 volts. Thus:

$$E_{av} = (E_{peak})(0.636)$$

This is shown in (a) of Figure 6 where both halves of the cycle are shown above the zero line so that they do not cancel.



(a) AVERAGE FULLWAVE = 0.637 x PK

(b) AVERAGE 1/2 WAVE = 0.318 x PK

(c) rms = 0.707 x PK

Figure 6 - Measurement techniques for sine waveforms.

CONVERSION CHART

The conversion between the various ac units of measurement are summarized in Table 5 below.

KNOWN	TO DERIVE, MULTIPLY BY			
	rms	peak	p-p	full-wave average
rms	----------	1.414 x rms	2.828 x rms	0.9 x rms
peak	0.707 x pk	----------	2 x pk	0.637 x pk
p-p	0.3535 x p-p	0.5 x p-p	----------	0.3185 x p-p
average	1.11 x av	1.57 x av	3.14 x av	----------

TABLE 5 - Conversion factors for ac units.

From the above it is possible to determine that the 120 volt power line outlet in the home or shop provides the following ac voltages as measured in rms, average, peak and peak-to-peak.

E_{rms} = 120 vac
E_{pk} = 120 x 1.414 = 169.68 or 170 V
$E_{p\text{-}p}$ = 120 x 2.828 = 339.36 or 340 V
E_{av} = 120 x 0.9 = 108 V

CONCLUSIONS

We have learned from this information sheet that:

Power distribution systems are virtually all ac today and use transformers to step the ac voltages up and down in value.

Ac generators are constructed the same as dc generators except that slip rings are used to connect to the armature rather than a commutator.

The output waveshape of the ac generator is a sine wave. It is called this because the voltage level at any degree of rotation is a function of the sine of that angle.

The instantaneous voltage for any point in a sine wave is given by

$$e = E_m \sin \Theta$$

A sine wave consists of one positive and one negative alternation. Two consecutive alternations make up one cycle.

One cycle, being generated by one rotation of the generator armature is, like a circle, divided into 360 degrees.

The time required to complete one cycle of an ac waveform is called the Period and is measured in seconds.

The number of ac cycles completed in one second is called the Frequency and is measured in hertz.

Frequency and Period (time) are related by

$$f = 1/T \quad \text{or} \quad T = 1/f$$

The ac spectrum is divided into segments labeled Very Low Frequencies (vlf) to Extremely High Frequencies (ehf).

High frequencies notation is simplified by the use of scientific or engineering notation. Most often used are

1,000 Hz = 1 kilohertz = 1 kHz = 10^3 Hz
1,000,000 Hz = 1 megahertz = 1 mHz = 10^6 Hz
1,000,000,000 Hz = 1 gigahertz = 1 gHz = 10^9 Hz

Sine wave ac voltages may be measured in four different ways

E_{peak}	E_{rms}
$E_{peak\text{-}to\text{-}peak}$	$E_{average}$

The ac rms measurement is the equivalent in power of a dc voltage of the same value.

An ac voltage or current is rms unless otherwise noted.

Ac voltages can be converted from one form to another by the use of the correct multipliers.

ASSIGNMENT

Answer the following True-False questions.

1. Most power distribution systems provide ac rather than dc. ____

2. The ac voltages that are distributed by the power companies can be raised and lowered using transformers. ____

3. When an ac voltage is applied to a load, current flows in one direction for the first alternation and then in the other direction for the second alternation. ____

4. An ac generator is constructed much the same as a dc generator except that the voltage take-off from the armature of the ac generator uses a commutator rather than slip rings. ____

5. The output of an ac generator is called a sine wave because it varies at a cosine rate. ____

6. Two successive alternations of a sine wave create one cycle. ____

7. The instantaneous voltage of a sine wave, that has an rms of 70.7 volts, at 67 degrees is approximately 92 volts. ____

8. A sine wave that has a period of 2 milliseconds has a frequency of 5 kHz. ____

9. If the positive peak of a sine wave measures 30 volts, the negative peak of the same sine wave can measure anywhere between 28 to 31 volts negative. ____

10. An ac voltage with a frequency of 25,000 Hz has a period of 0.04 milliseconds. ____

11. A frequency of 750,000 Hz can be represented as 0.75 mHz or 75 kHz. ____

12. A sine wave that has an rms voltage of 140 has a peak voltage of approximately 198 volts. ____

13. A sine wave with a peak-to-peak voltage of 220 volts has an rms voltage of 110 volts. ____

14. The average voltage of a complete sine wave that has a peak voltage of 100 volts is 63.7 volts. ____

15. A sine wave with a peak-to-peak voltage of 250 volts has a peak of 125 volts, an rms of 88.4 volts and an average of approximately 80 volts. _____

16. The average voltage of a full sine wave is zero. _____

17. a. Draw one cycle of a sine wave.

b. Mark off the time base in degrees.

18. Draw one cycle of a sine wave with a peak value of 100 volts. Calculate and mark off the following:

a. peak-to-peak voltage
b. rms voltage
c. average voltage
d. peak voltage

KEY TERMS

1. ALTERNATING CURRENT (ac)

   A flow of electrons in one direction that reaches a maximum value, drops to zero, then reverses direction, again increasing to a maximum value and dropping to zero again. Two complete alternations create a cycle which is repeated continuously.

2. ALTERNATING VOLTAGE (acv)

   A voltage that varies in value and reverses polarity at regular intervals.

3. ALTERNATION

   One half of a cycle. One positive and one negative alternation forms one cycle.

4. AVERAGE VOLTAGE (E_{av})

   The average value of an ac voltage or current is determined by adding the instantaneous voltage values of one alternation every degree and averaging them. It will be equal to the peak voltage multiplied by 0.637.

5. CYCLE

   The changing of a voltage or current from zero to a positive peak, back to zero, to a negative peak and back to zero again. Two alternations complete a cycle.

6. E_{ac}

   The effective or rms voltage value.

7. EFFECTIVE VOLTAGE (E_{ac} , E_{eff} , E_{rms})

   The value of ac that will produce the same heating effect in a resistance as a value of dc. Also called the root mean square or rms voltage.

8. EXTREMELY HIGH FREQUENCY (ehf)

   The frequency range from 30,000 mHz to 300,000 mHz.

9. FREQUENCY (f)

   The number of recurrences of a cycle in one second, measured in hertz.

10. GIGAHERTZ (gHz)

    One trillion (1,000,000,000 or 10^9) hertz.

11. HIGH FREQUENCY (hf)

The frequency range from 3,000 kHz to 30,000 kHz.

12. INSTANTANEOUS VOLTAGE (e, e_{inst})

The magnitude of the ac voltage at any angle during the cycle. It is calculated from $e = e_m \cdot \sin \Theta$.

13. KILOHERTZ (kHz)

One thousand hertz.

14. LOW FREQUENCY (lf)

The frequency range from 30 kHz to 300 kHz.

15. MAXIMUM VOLTAGE (E_{max})

The highest value of voltage that occurs during one alternation of a cycle. Also called the peak voltage, E_p.

16. MEDIUM FREQUENCY (mf)

The frequency range from 300 kHz to 3,000 kHz.

17. MEGAHERTZ (mHz)

One million hertz.

18. PEAK VOLTAGE (E_p)

See Maximum Voltage.

19. PEAK-TO-PEAK VOLTAGE (E_{p-p})

The value of an alternating voltage measured from the positive to negative peaks of the ac wave.

20. PERIOD

Time, in seconds, required to complete one cycle of an ac waveform.

21. ROOT MEAN SQUARE VOLTAGE (rms)

See Effective Voltage.

22. SUPER HIGH FREQUENCY (shf)

The range of frequency from 3,000 mHz to 30,000 mHz.

23. ULTRA HIGH FREQUENCY (uhf)

The range of frequencies from 300 mHz to 3,000 mHz.

24. VERY HIGH FREQUENCY (vhf)

The range of frequency from 30,000 kHz to 300 mHz.

25. VERY LOW FREQUENCY (vlf)

The range of frequency from dc to 30 kHz.

Measuring AC Voltages 2

OBJECTIVES

When you finish this experiment, you will be able to:

1. Measure ac voltages with the Ed-Lab panel meter.
2. Measure ac voltages with an external VOM or Electronic Multimeter (Optional).
3. Determine that ac rms voltages are the equal of dc voltages.
4. Determine that ac voltages in resistive circuits are subject to Ohm's Law.

ADDITIONAL EQUIPMENT

VOM or Electronic or Digital Multimeter (Optional)

DESCRIPTION

When dc voltages and currents were measured in earlier experiments, it was necessary to observe the meter polarity when connecting into a circuit. Reversal of the meter polarity caused the pointer to slam backwards against the stop. With proper connection, the direction of flow was correct, the amount of current flow through the meter was constant and the meter provided an exact reading of the voltage.

The measurement of ac voltages and current presents a different problem. The voltage and current levels are constantly changing and the polarity is constantly reversing as well. In a previous experiment when we tried to measure ac voltage with a dc meter, the meter pointer started to swing up-scale on the positive alternation. Before the pointer moved very far, the peak positive voltage passed, the polarity reversed and the pointer then tried to swing backwards to measure the negative alternation. The result was that the meter pointer hovered around the zero setting and vibrated at a rate determined by the ac frequency or it could not be seen to move at all at higher frequencies.

To be able to measure ac, the dc meter must be modified by the addition of the diodes. The purpose of the diodes is to change the ac to dc which the meter can then read. This is all presented in more detail later.

AC VOLTAGES AND METERS

The sinusoidal ac voltages have several measurements as discussed in Information Sheet 2 and reviewed below in Figure 1.

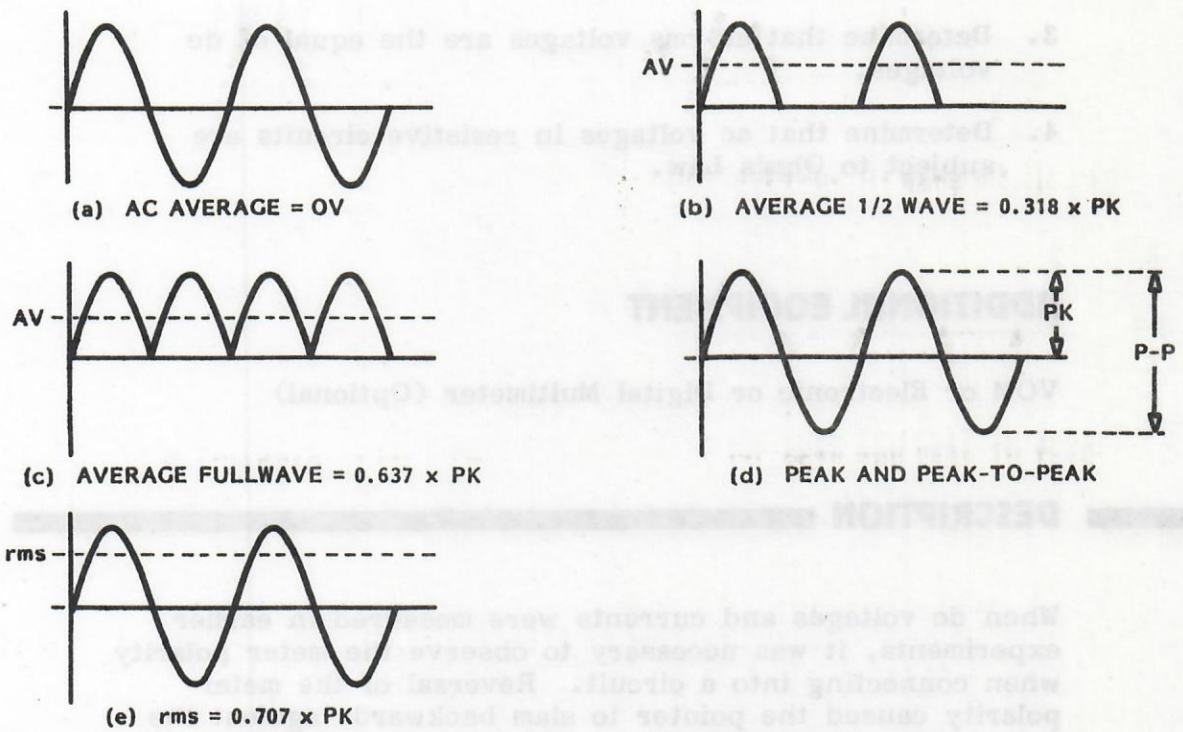
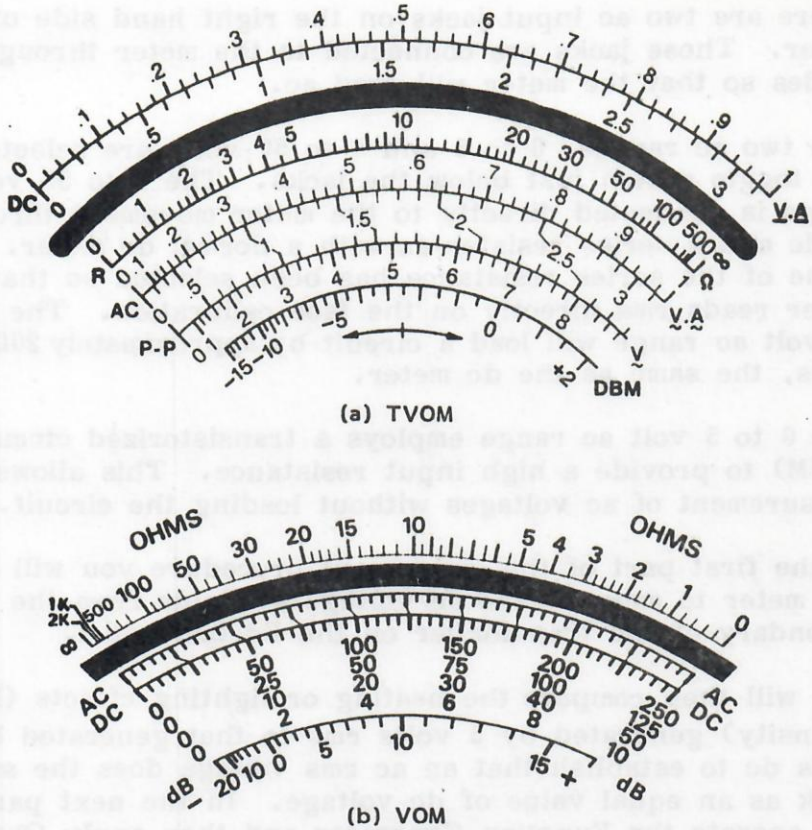


Figure 1 - Comparison of sinewave measurements.

The ac meters are calibrated to read in rms unless marked otherwise. Also, because of certain diode characteristics, the ac scales are often non-linear. To correct this problem, the ac scales on the meter face are printed separately, usually in red, with corrections for the non-linearity. Two typical meter faces are shown in Figure 2. One meter face (a) is from an Electronic Transistor multimeter (TVOM) and (b) is the meter face of a VOM multimeter.



(a) TVOM

(b) VOM

Figure 2 - Typical meter scales illustrating the non-linearity of the ac calibration

The ac ranges of the Ed-Lab panel meter are 0 to 5 and 0 to 50. The Ed-Lab meter face is shown below in Figure 3.

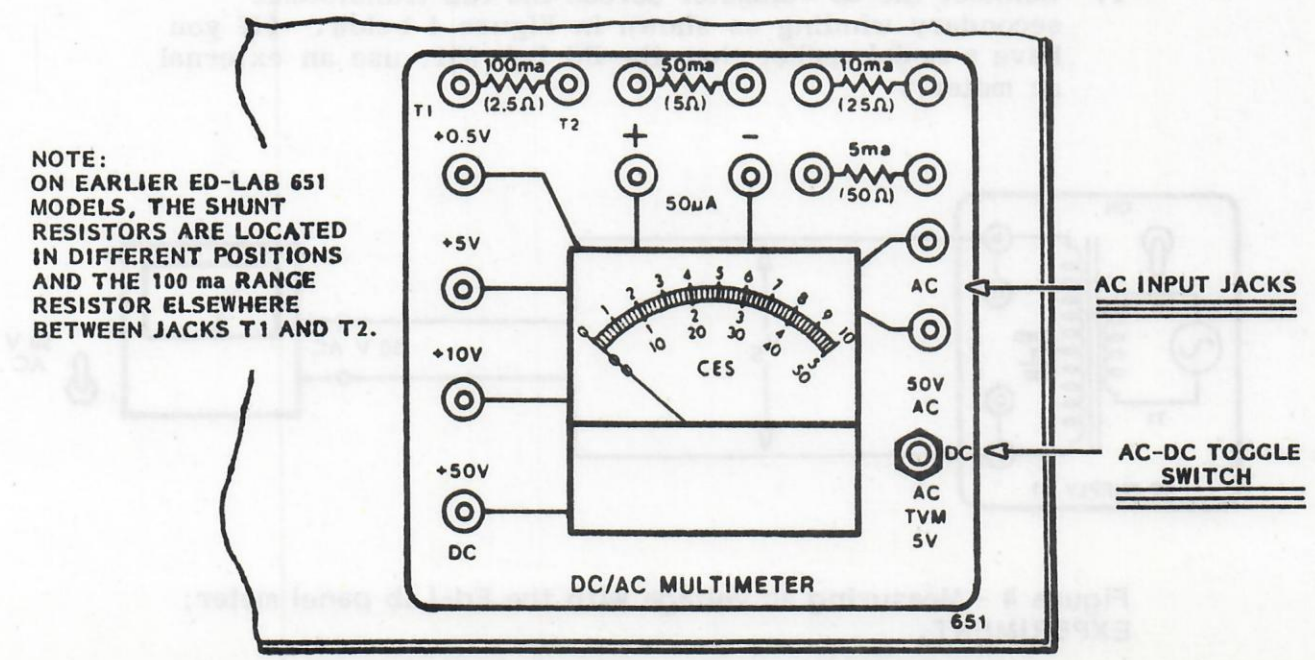


Figure 3 - Ed-Lab panel meter.

There are two ac input jacks on the right hand side of the meter. These jacks are connected to the meter through diodes so that the meter will read ac.

The two ac ranges, 0 to 5 and 0 to 50 volts are selected by the toggle switch just below the jacks. The 0 to 50 volt range is connected directly to the meter movement through a diode and a series resistor as with a normal dc meter. The value of the series resistance has been selected so that the meter reads rms directly on the face calibration. The 0 to 50 volt ac range will load a circuit by approximately 200K ohms, the same as the dc meter.

The 0 to 5 volt ac range employs a transistorized circuit (TVM) to provide a high input resistance. This allows measurement of ac voltages without loading the circuit.

In the first part of the experiment procedure you will use the meter to measure the ac voltage available from the secondary of the transformer on the Ed-Lab panel.

You will then compare the heating or lighting effects (lamp intensity) generated by 5 volts rms to that generated by 5 volts dc to establish that an ac rms voltage does the same work as an equal value of dc voltage. In the next part, you will operate the Function Generator and then apply Ohm's Law to a resistive ac circuit.

PROCEDURE

1. Connect the ac voltmeter across the full transformer secondary winding as shown in Figure 4 below. (If you have a model earlier than the Ed-Lab 651, use an external ac meter.)

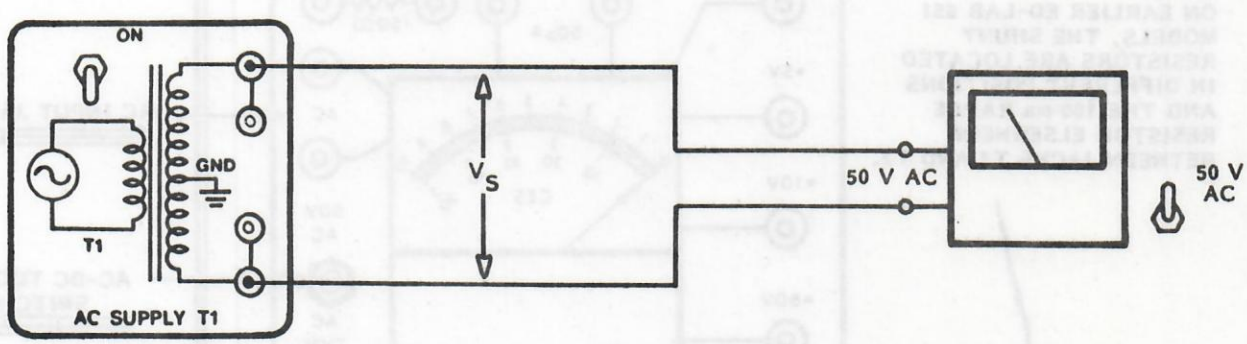


Figure 4 - Measuring ac voltage with the Ed-Lab panel meter; EXPERIMENT.

Be sure to use the two ac jacks and place the switch in the UP position to 50 VAC. Be certain, also, to read the 0 to 50 scale.

2. Read and record the output voltage of the full power transformer secondary.

V_S = _____ V_{AC}

3. The power line input frequency is 60 Hertz and the voltage is 120 volts. The transformer is a STEP-DOWN type and you can calculate the turns ratio of the transformer.

TURNS RATIO $\quad TR = \frac{120}{V_S} = \frac{120}{(\quad)}$

TURNS RATIO	TR = _____ : 1

4. The transformer secondary is center-tapped and the voltage across each half of the winding should read half of the full secondary voltage. The center-tap of the transformer is connected to ground and you can make connection to it at the ground bus at the top of the trainer.

Read the voltage of the upper half of the secondary as shown in Figure 5 and enter the reading on the next page.

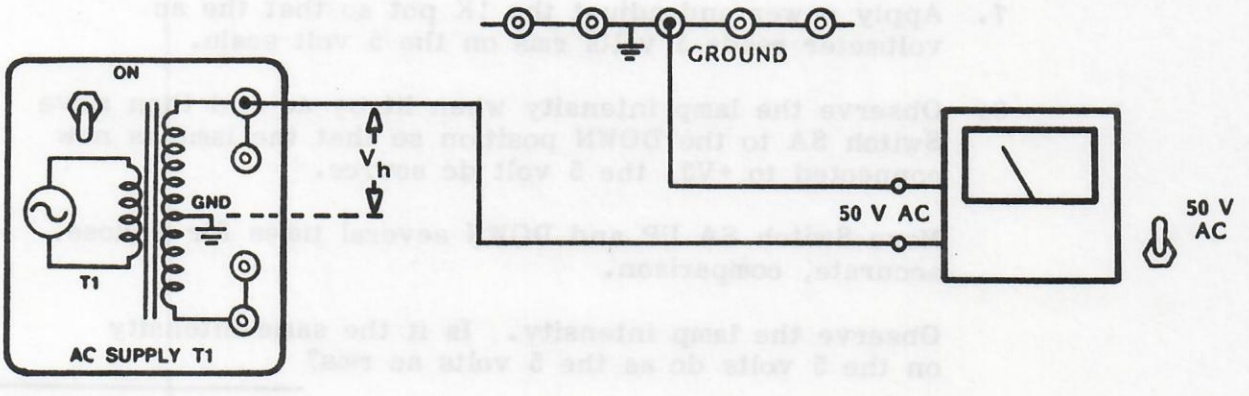


Figure 5 - Ac meter reading of one half of the transformer secondary; EXPERIMENT.

V_h = _____ Vac

Remember, all these voltages are rms.

2.1 COMPARING AC RMS TO DC

5. Wire the circuit shown in Figure 6.

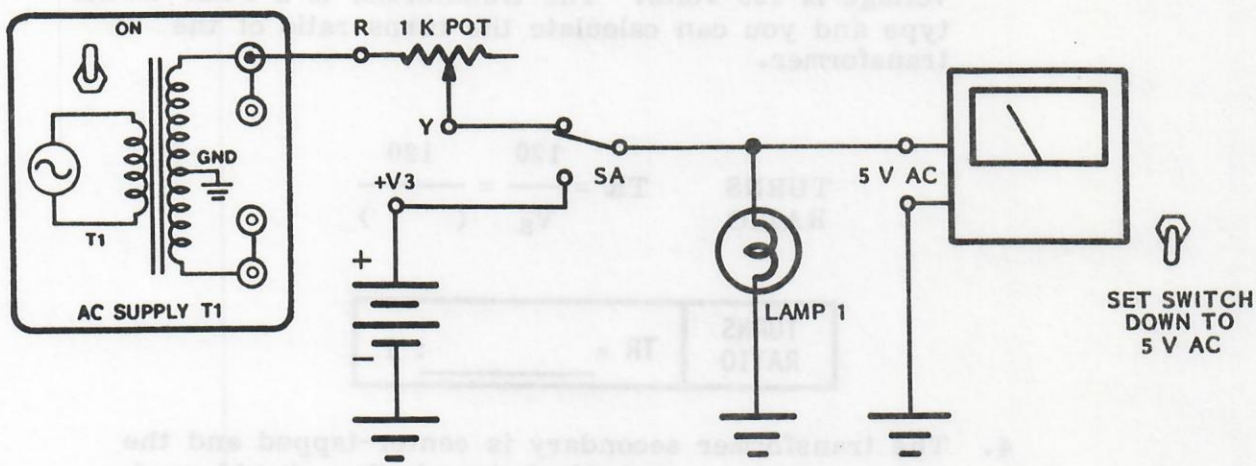


Figure 6 - Circuit used to compare dc to an equivalent rms voltage; EXPERIMENT.

6. Set the 1 K pot fully CCW for maximum resistance.

   Set Switch SA in the UP positon so that the lamp filament will be heated by the ac voltage from transformer T1.

7. Apply power and adjust the 1K pot so that the ac voltmeter reads 5 volts rms on the 5 volt scale.

8. Observe the lamp intensity when lit by ac and then move Switch SA to the DOWN position so that the lamp is now connected to +V3, the 5 volt dc source.

   Move Switch SA UP and DOWN several times for a close, accurate, comparison.

   Observe the lamp intensity. Is it the same intensity on the 5 volts dc as the 5 volts ac rms?

   _____

   This shows that the 5 volts ac rms has the same power as 5 volts dc.

2.2 SIGNAL GENERATOR VOLTAGES

9. Measure the ac voltage from the sinewave output of the Function Generator using the ac meter. Wire the circuit shown in Figure 7.

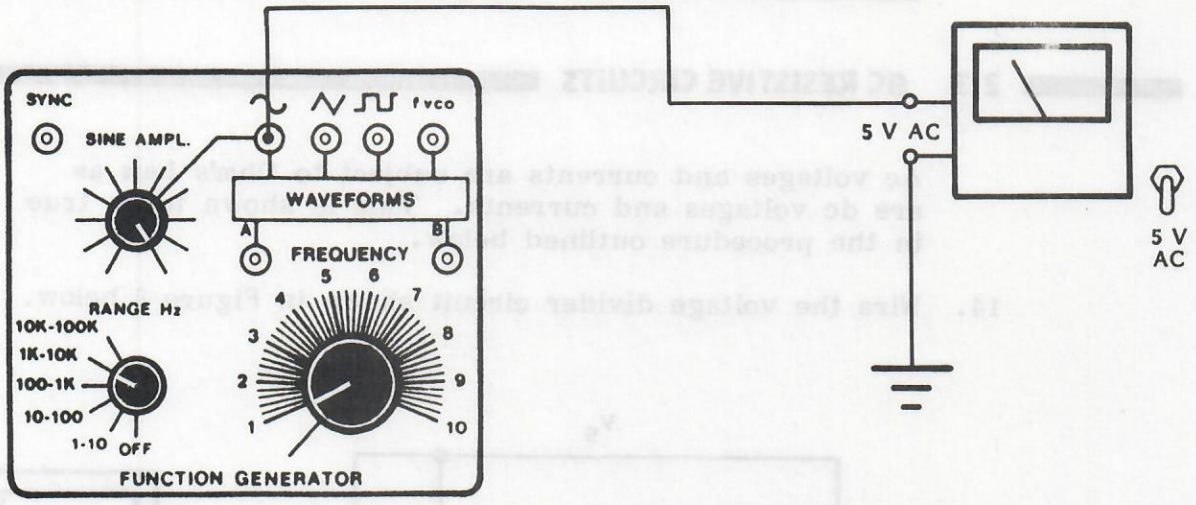


Figure 7 - Ac voltmeter connected to the sinewave output of the Function Generator; EXPERIMENT.

10. Set the Function Generator controls as shown in Figure 7.

SINE AMPL. - FULL CLOCKWISE
RANGE Hz - 1 K to 10 K
FREQUENCY - 1

This provides an ac output voltage from the Function Generator of 1 kHz. (1,000 Hz).

11. Vary the SINE AMPL control and observe the meter.

What is the maximum output voltage?

V_{max} _____ rms

12. Adjust the sinewave amplitude to 3 volts.

The rms calibration for this or any ac meter is true for sinusoidal (sine wave) voltages only.

The SINE AMPL control knob affects the sinewave output only.

13. Vary the frequency control from 1 to 10 that is from 1 kHz to 10 kHz while observing the meter.

Does the meter read the rms voltage for any frequency through the 1 kHz to 10 kHz range? _____

2.3 AC RESISTIVE CIRCUITS

Ac voltages and currents are subject to Ohm's Law as are dc voltages and currents. This is shown to be true in the procedure outlined below.

14. Wire the voltage divider circuit shown in Figure 8 below.

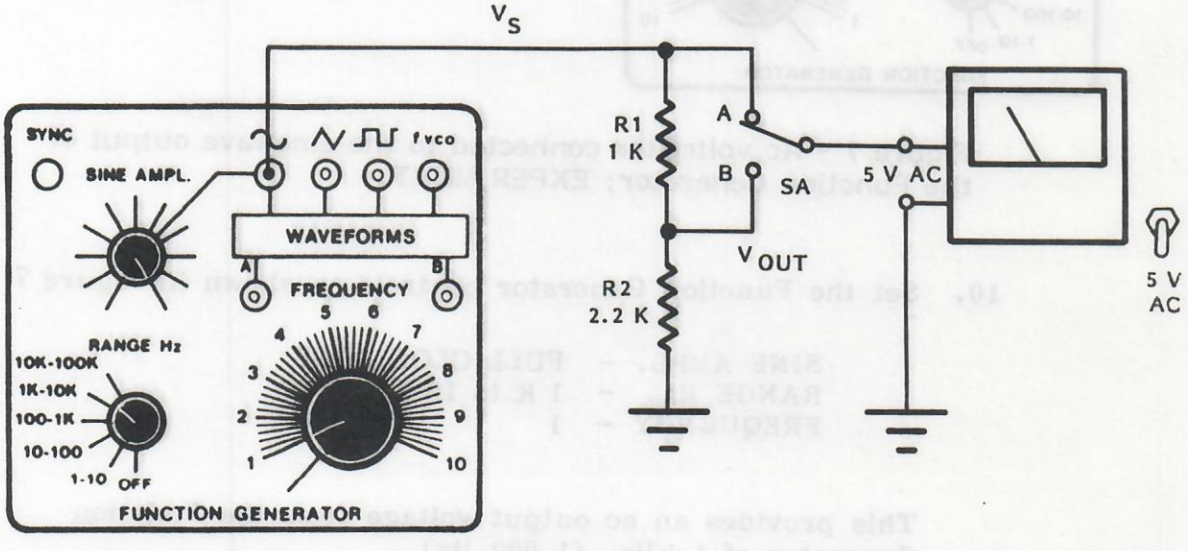


Figure 8 - Ac voltage divider EXPERIMENT.

15. Set Switch SA UP to measure the ac input to the voltage divider and adjust the value so that V_S equals 3 volts.

16. Calculate the expected ac output voltage at B of Figure 8 using the Voltage Divider Formula used earlier in Unit E4 in dc.

$$V_{out} = (V_S) \frac{R_2}{R1 + R2}$$

where V_S is the input voltage measured in step 15, 3 volts.

$$V_{out} = (3)\frac{2.2}{1 + 2.2} = (3)\frac{2.2}{3.2}$$

$V_{out\ calculated}$ _____ Vac

17. Measure the voltage divider output from point B by placing Switch SA DOWN. Record the output voltage below.

$V_{out\ measured}$ _____ Vac

18. Vary the frequency from 1 kHz to 2, 3, 5 and 6 kHz and observe the output voltage.

Does the output voltage change as the input frequency changes? _____

_____

What can you conclude about the behavior of ac and dc voltage in a resistive circuit and the application of Ohm's Law? _____

_____

2.4 VOM AND ELECTRONIC AND DIGITAL MULTIMETERS (OPTIONAL)

19. Select a meter to be used to measure ac voltages on the trainer and list the following data for it.

a. Manufacturer _____

b. Model No. _____

c. Meter Type (VOM, etc.) _____

d. Number of ac Scales _____

e. AC Voltage Scale Ranges

0 to _____ Vac	0 to _____ Vac
0 to _____ Vac	0 to _____ Vac
0 to _____ Vac	0 to _____ Vac
0 to _____ Vac	0 to _____ Vac

f. DC Voltage Scale Ranges

0 to _____ Vdc	0 to _____ Vdc
0 to _____ Vdc	0 to _____ Vdc
0 to _____ Vdc	0 to _____ Vdc
0 to _____ Vdc	0 to _____ Vdc

Does the meter face have different ac and dc scale calibrations?

_____

20. Set up the external meter to measure ac voltage using a range close to but greater than 5 volts full scale.

Range = 0 to _____ Vac

21. Disconnect the two wires connected to the ac meter on the panel and connect them to the external meter as shown in Figure 9 below.

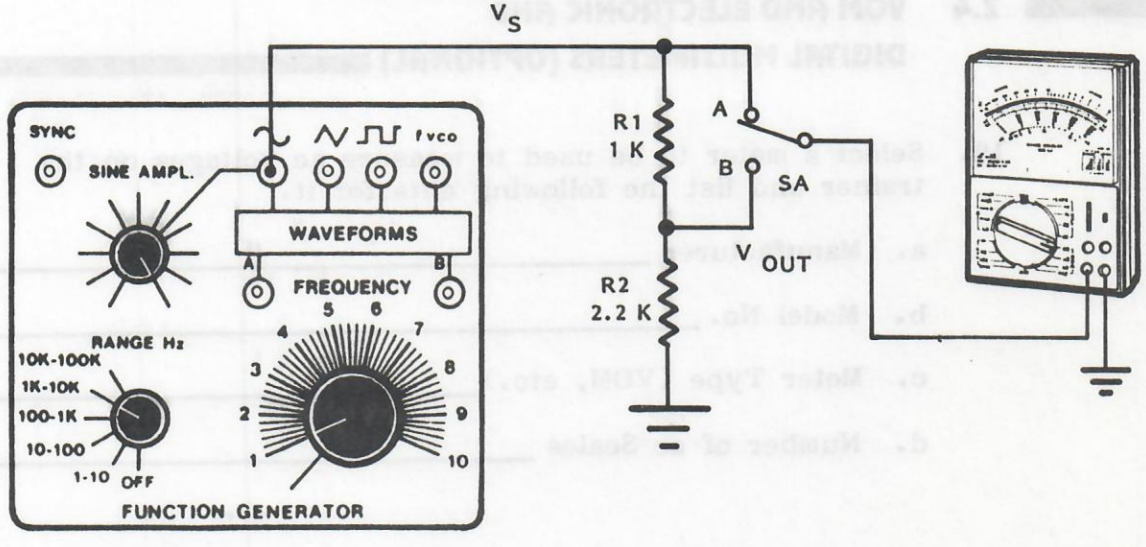


Figure 9 - Ac voltage measurement with an external ac meter; EXPERIMENT.

With Switch SA UP adjust V_S to 3 volts.

Place Switch SA DOWN, read the divider output voltage and record it below.

V_{out} = _____ Vac

CONCLUSIONS

We have learned from this experiment that:

When measuring ac voltages and currents with a meter, it is not necessary to observe polarity when connecting into the circuit.

Ac voltages and currents are understood to be in rms unless otherwise noted.

Ac meter scales are calibrated in rms unless marked otherwise.

In most multimeters, the ac scales are non-linear and thus require a separate calibration. The greatest non-linearity is at the low end of the scale.

The ac rms value is equivalent to an equal value of dc.

Ac voltages and currents in a resistive circuit are governed by Ohm's Law.

ASSIGNMENT

Answer the following multiple choice questions.

1. When using a dc voltmeter to measure ac:

   a. polarity must be observed.
   b. the dc scale calibration becomes non-linear.
   c. the scale calibration must be doubled to compensate for the negative half cycle.
   d. none of the above.

2. To measure ac with a dc meter:

   a. no precaution is needed; it may be used directly.
   b. the scale reading must be doubled.
   c. diodes must be added to the meter circuit.
   d. none of the above.

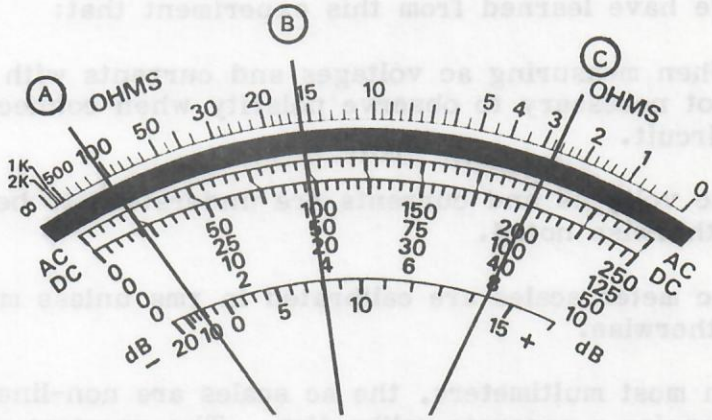


Figure 10 above refers to questions 3 to 5.

3. When the meter shown in Figure 10 is set to the 250 volt ac range, the voltage reading for position A of the pointer is closest to:

   a. 100 volts.
   b. 25 volts.
   c. 22 volts, approximately.
   d. 5 volts.

4. When the meter in Figure 10 is set on the 125 volt ac range the B position of the pointer indicates exactly:

   a. 50 volts.
   b. 49 volts.
   c. 15 volts.
   d. 4 volts.

5. When the meter in Figure 10 is set on the 250 volt ac range the C position of the pointer indicates:

   a. exactly 200 volts.
   b. slightly more than 200 volts.
   c. 100 V.
   d. 40 V.

6. An ac voltage of 60 volts is equal to:

   a. 60 volts rms.
   b. 84.84 volts peak.
   c. 60 volts dc.
   d. all of the above.

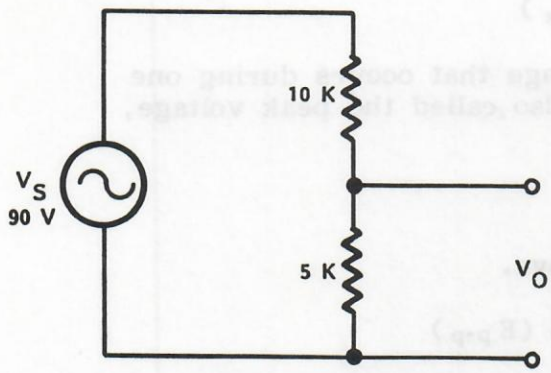


Figure 11.

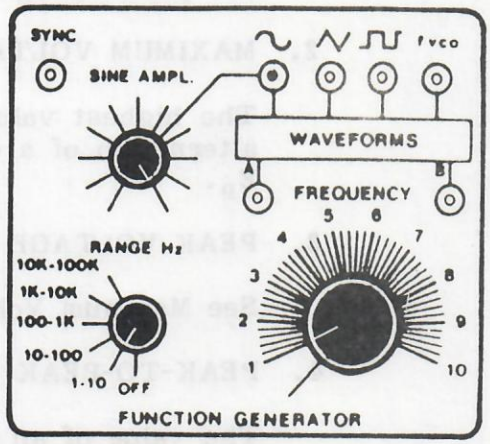


Figure 12.

7. In Figure 11, V_O is equal to:

   a. 90 volts.
   b. 60 volts.
   c. 30 volts.
   d. 15 volts dc.

8. A dc voltage of 50 volts is equal to an ac voltage of:

   a. 50 volts rms.
   b. 70.7 volts peak.
   c. 141.4 pp.
   d. all of the above.

9. If, in Figure 12 above, the RANGE Hz knob of the Function Generator were switched from the position shown to 1K - 10K, with all other controls remaining set, the output frequency will change to:

   a. 10 Hz.
   b. 1 kHz.
   c. 10 kHz.
   d. remain unchanged.

10. Voltage distribution in resistive circuits powered by ac:

   a. may be calculated using Ohm's Law.
   b. is not the same as when powered by dc.
   c. is non-linear.
   d. all of the above.

KEY TERMS

1. AVERAGE VOLTAGE (E_{av})

   The average value of an ac sine wave alternation is determined by adding the instantaneous values of voltage every degree and averaging them. It will be equal to the peak voltage multiplied by 0.637.

2. MAXIMUM VOLTAGE (E_{max})

   The highest value of voltage that occurs during one alternation of a cycle. Also called the peak voltage, E_p.

3. PEAK VOLTAGE (E_p)

   See Maximum Voltage, above.

4. PEAK-TO-PEAK VOLTAGE (E_{p-p})

   The value of an alternating voltage measured from the positive peak to the negative peak of the ac wave.

5. ROOT MEAN SQUARE (rms)

   The value of ac voltage or current that will produce the same heating effect in a resistance as a value of dc. Also called the Effective Voltage, V_{eff}.

Capacitors

INFO SHEET 3

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Draw the construction of a basic capacitor.
2. Explain the charge-discharge action of a capacitor.
3. Describe the electrostatic field generated in a capacitor and its effect on the dielectric atoms.
4. Define what is meant by a capacitor's Working Voltage.
5. Convert capacitor values from farads to microfarads to micromicrofarads.
6. Calculate the capacitor charge in coulombs.
7. Calculate the capacitance of a capacitor given the required data.
8. Calculate the energy stored in a capacitor.
9. Calculate the total capacitance and working voltage for series and parallel capacitor combinations.
10. Describe the construction of electrolytic capacitors and variable capacitors.

DESCRIPTION

In or about the year 1715, the LEYDEN jar was invented in the town of Leyden, Holland, by Pieter Van Musschenbroek. This was the first device that could store electricity and so allowed the scientist of that period to perform experiments with useable "dynamic" rather than static electricity. The modern CAPACITOR was developed from the Leyden jar but for several hundred years it was called a CONDENSER. It was thought that the capacitor "condensed" electricity thus allowing it to be stored.

CAPACITORS

Every electronic circuit no matter how simple or complex, contains some or all of the three basic components; resistors, capacitors and inductors.

A capacitor consists of two conductors separated by an insulator called a DIELECTRIC. The capacitor shown in Figure 1(a) has air as a dielectric and has the property of CAPACITANCE which means that it has the "capacity" to store an electrical charge. The charge stored in this capacitor maintains a corresponding voltage and will oppose any change in voltage in the circuit in which it is connected.

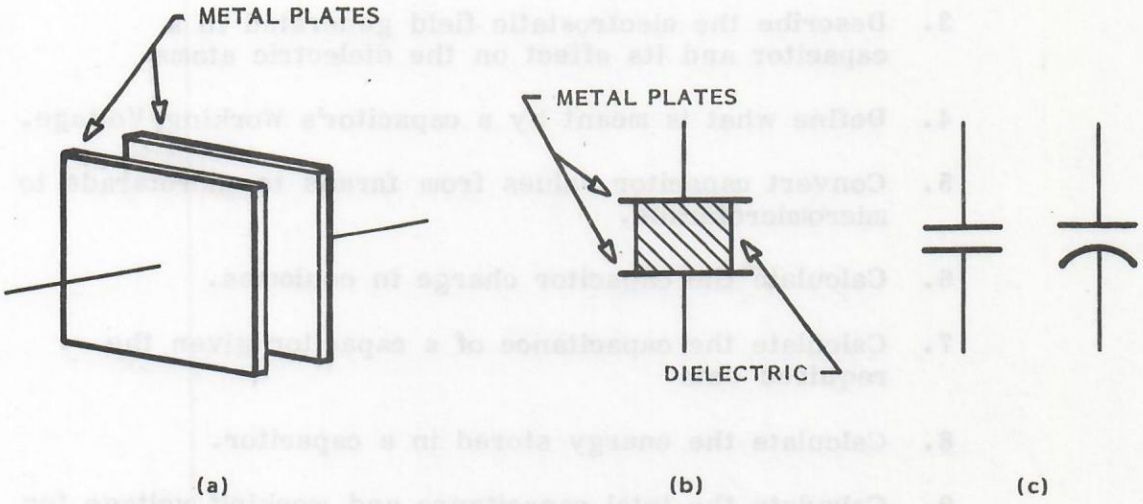


Figure 1(a) and (b) - Capacitor construction. (c) - Capacitor symbols.

The simplest type of capacitor construction consists of two metal plates separated by air which is an insulator and acts as the dielectric. The dielectric may also be mica, glass, ceramic or any other suitable insulating material.

CHARGING ACTION

When a capacitor is connected across a voltage source, as shown in Figure 2, electrons leave the negative terminal of the voltage source, flow through the connecting wire and enter the capacitor plate A.

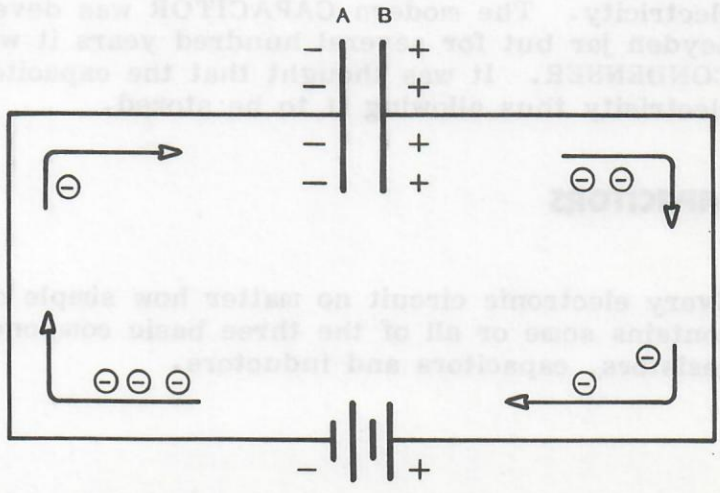


Figure 2 - Capacitor charging action.

For each electron that enters plate A, one electron is repelled from plate B to flow back to the positive terminal of the voltage source. This process continues and as the negative charge on plate A builds up, it becomes more difficult for additional electrons to enter the plate. Finally, the capacitor charge is so great that no more electrons can enter plate A and so no more electrons leave plate B.

As the electrons enter plate A and leave plate B of the capacitor, a difference of potential or voltage is built up. When the capacitor's difference of potential rises to equal the source voltage, all electron flow stops and the capacitor is CHARGED.

ELECTROSTATIC FIELD

You will recall from Information Sheet 3, Voltage Sources, Unit E1, that a difference of potential between two conductors, such as shown in Figure 3(a), creates an ELECTRIC FIELD also called an ELECTROSTATIC FIELD, whose lines of force run from plus to minus.

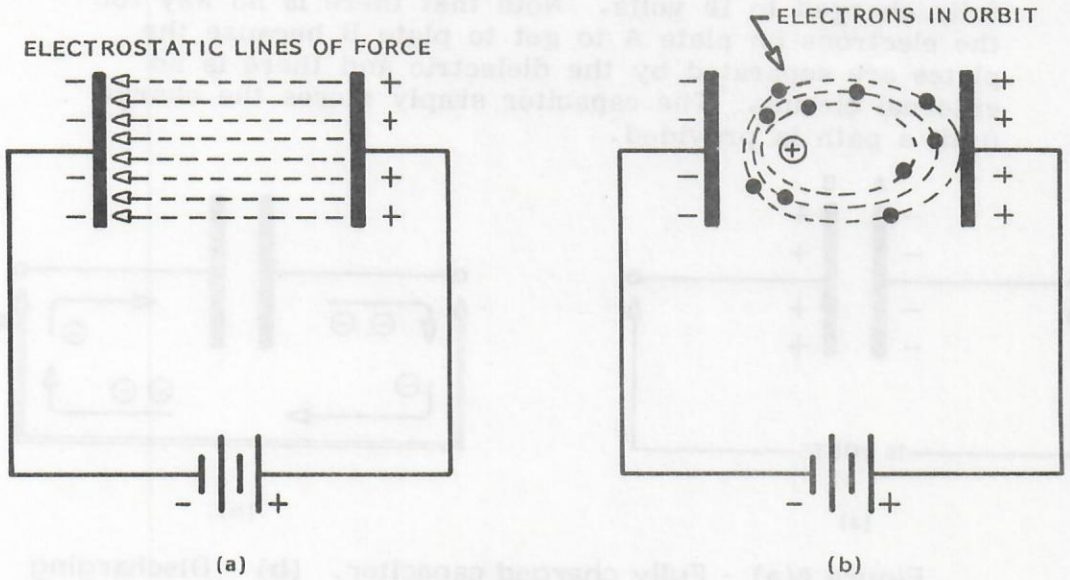


Figure 3(a) - Electrostatic lines of force in a charged capacitor. (b) - Distortion of an atom in the dielectric.

The atoms in the dielectric of a charged capacitor become distorted as shown in Figure 3(b). The positive nucleus of the atom is drawn towards the negative plate and the orbiting electrons (negative charges) are drawn toward the positive plate and repelled by the negative plate. This

results in eliptical orbits of the electrons around the nucleus as shown in Figure 3(b). The electrons in the atoms of the dielectric are tightly held in orbit because the dielectric material is an insulator which does not free electrons for conduction easily.

WORKING VOLTAGE

If the charging voltage applied to the capacitor is made high enough, the electric field will get so strong that it will tear those electrons in the outer ring (valence electrons) loose from their atoms, thus destroying the capacitor by allowing an electron flow between the plates. For this reason, every capacitor has a maximum voltage rating called the WORKING VOLTAGE, abbreviated WV.

CAPACITOR DISCHARGE ACTION

To discharge a capacitor, that is to remove the electron charge from the plates, the net charges on each plate must be neutralized or made equal. This means that the excess of electrons on the negatively charged plate must be removed and the shortage of electrons on the positive plate must also be corrected. The capacitor shown in Figure 4(a) is fully charged to 10 volts. Note that there is no way for the electrons on plate A to get to plate B because the plates are separated by the dielectric and there is no external circuit. The capacitor simply stores the charge until a path is provided.

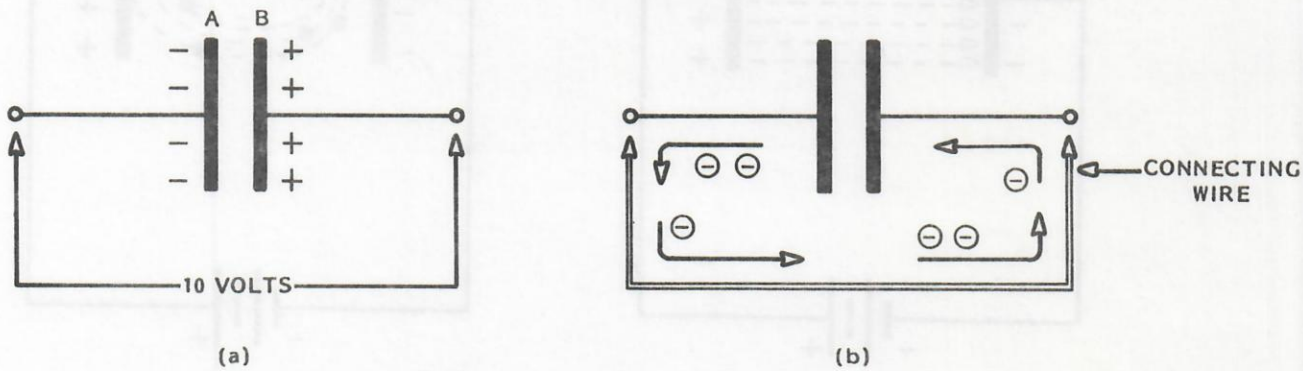


Figure 4(a) - Fully charged capacitor. (b) - Discharging the capacitor.

When an external conductor or wire is connected across plates A and B, as shown in Figure 4(b), the excess of electrons on plate A flow to the positive plate B and both charges are neutralized. When the capacitor is discharged, the orbiting electrons in the dielectric give up their distorted orbits and return to normal and any energy stored in the dielectric returns to the circuit. When completely discharged, there is no longer any measurable voltage across the capacitor.

CAPACITIVE UNITS

Capacitance is measured in a unit called the FARAD after Michael Faraday (1791-1869) who did much basic research in electrostatics and magnetism. The farad (F) is a very large unit and practical values of capacitance must be expressed using the metric prefixes of micro and pico. The microfarad (mF or μF) is $Fx10^{-6}$ and the picofarad (pF) is $Fx10^{-12}$. The picofarad is often referred to as the micromicrofarad (mmF or $\mu\mu$F).

The honor of naming the capacitive unit should really have gone to Pieter Van Musschenbroek, inventor of the Leyden jar, but who could pronounce "one micromicromusschenbroek?"

RATE OF VOLTAGE CHANGE

A capacitor has a capacitance of 1 farad when the voltage across its plates rises at a rate of 1 volt per second when 1 ampere is flowing.

This can be expressed as:

$$1 \text{ farad} = \frac{\text{charging current of 1 ampere}}{\text{voltage rise of 1 volt in 1 second}}$$

The value of capacitance in farads can be defined in a number of ways shown in the formulas below. Each formula is discussed in the following paragraphs,

$$C = \frac{i}{\frac{\Delta V}{\Delta t}}$$

C = capacitance in farads
ΔV = voltage change, in volts
Δt = time change, in seconds
i = charging current in amperes

(a) By rate of change of voltage for a given current.

$$C = \frac{Q}{V}$$

Q = charge in coulombs
C = capacitance in farads
V = applied voltage in volts

(b) By the ratio of charge to voltage.

$$C = \frac{Ak}{d}$$

C = capacitance in picofarads
A = area of one plate
d = distance between plates
k = dielectric constant of the insulator

(c) By physical dimensions.

The farad, as expressed by the "rate of change" formula is illustrated by an example on the next page.

$$C = \frac{i}{\frac{\Delta V}{\Delta t}}$$

where C = Capacitance, in farads, F
ΔV = voltage change, in volts
Δt = time change, in seconds
i = charging current in amperes

Using the above formula to determine the capacitance, C, for a capacitor that has a charging current of 0.0004 amperes, resulting in a ΔV of 1 volt in a Δt of 0.25 seconds, we have:

$$C = \frac{i}{\frac{\Delta v}{\Delta t}}$$

$$= \frac{0.0004}{\frac{1}{0.25}}$$

$$c = 0.0001 \text{ farads}$$

$$= 0.0001 \times 10^{-6} \ \mu F$$

$$C = 100 \ \mu F$$

CAPACITOR CHARGE

The charge that accumulates on the capacitor's plates is a function of the applied voltage (V) and the capacity in farads (F). A 1 farad capacitor will store 1 coulomb of charge when connected across a 1 volt source. Recall from Information Sheet 4, Current Flow, Unit E1, that a coulomb is equal to 6.25×10^{18} electrons. This means that when the voltage applied to a 1 farad capacitor is increased from 1 to 2 volts, the charge increases from 1 to 2 coulombs, or to 12.5×10^{18} electrons. This may be expressed mathematically as:

$$Q = CV$$

where Q = charge in coulombs
C = capacitance in farads
V = applied voltage in volts

To find the charge in coulombs on a 10 μF capacitor connected across a 20 volt charging source, we have:

$$Q = CV$$

$$= (10 \times 10^{-6})(20)$$

$$\boxed{Q = 200 \times 10^{-6} \text{ coulombs}}$$

Because each coulomb is equal to 6.25×10^{18} electrons, the number of electrons (Ne) stored in the capacitor plate is given by

$$Ne = Q\ (6.25 \times 10^{18})$$

$$= (200 \times 10^{-6})(6.25 \times 10^{18})$$

$$\boxed{Ne = 1.25 \times 10^{15} \text{ electrons}}$$

The three quantities in Q = CV can be transposed so that when any two are known, the third can be found. Thus, for a given charge and voltage, the capacitance is defined as

$$\boxed{C = \frac{Q}{V}}$$

If the charge and capacitance are known, the voltage can be determined from

$$\boxed{V = \frac{Q}{C}}$$

PHYSICAL FACTORS AFFECTING CAPACITANCE

The ability of a capacitor to store a charge is determined by its physical measurements, the plate area, A, and the separation between the plates, d. This is shown in Figure 5 on the next page.

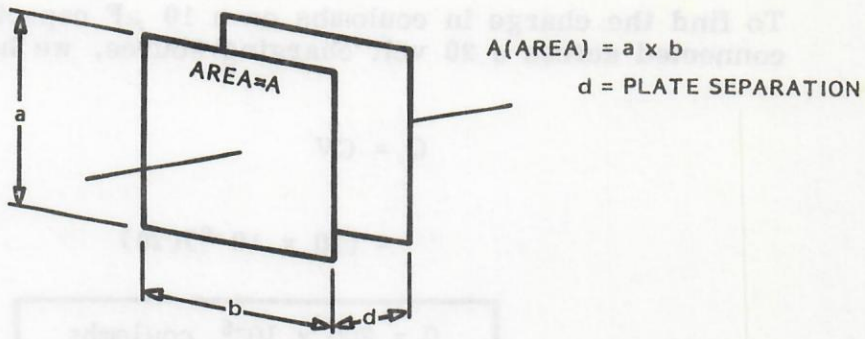


Figure 5 - Physical characteristics that determine capacitance.

Since the dielectric material determines the ease with which the electrons on one plate can affect the electrons on the opposite plate and the degree to which the dielectric can store energy in the form of stretched electron orbits, the dielectric characteristics are also a factor in determining capacitance. The dielectric constant, k, is defined by the ratio:

$$k = \frac{\text{capacitance with dielectric}}{\text{capacitance with vacuum dielectric}}$$

The dielectric constants for some commonly used materials are given in Table 1.

MATERIAL	CONSTANT
Vacuum	1.0000
Air	1.0006
Waxed Paper	2.1 - 2.3
Polyethelene	2.3
Polystyrene	2.4 - 2.5
Mica	2.5 - 7.0
Nylon	3.5
Neoprene	4.1
Porcelain	6.0 -8.0
Titanates (Bo, Sr, etc.)	15 - 12000

TABLE 1 - Dielectric constants.

The capacitance is directly proportional to the plate area and the dielectric constant but is inversely proportional to the plate separation, d, in Figure 5. Thus

$$C = \frac{Ak}{d}(0.2249)$$

where C = capacitance in picofarads (10^{-12}F)
A = area of one plate in square inches
d = distance between plates in inches
k = dielectric constant of the insulator
0.2249 = constant to convert from Metric to English units.

As an example, calculate the capacitance for the dimensions and dielectric constant given.

A = 10 square inches

d = 0.04 inches

k = 7 (porcelain)

$$C = \frac{Ak}{d}(0.2249)$$

$$= \frac{(10)(7)}{.04}(0.2249)$$

C = 394 picofarads or
C = 0.000394 microfarads

If, in the above example, all dimensions remained the same but an improved dielectric of Titanium dioxide with a dielectric constant of 100 is now used, the new capacitance is:

$$C = \frac{(10)(100)}{.04}(0.2249)$$

C = 5622 pF or
C = 0.0056 μF

This remarkable increase in capacitance (approximately 14 times more) was obtained through the use of a superior dielectric.

To calculate the capacitance C, in SI units, the formula is

SI UNITS	$C = \frac{Ak}{d} (884 \times 10^{-6})$

where C = capacitance in Farads
A = area of one plate cm^2
d = distance between plates in cm
k = dielectric constant

ENERGY STORAGE

The voltage source that charges the capacitor provides the electrical energy that is stored in the dielectric. It is this stored energy that provides the discharge current flow when the source voltage is removed and the capacitor terminals are shorted to each other. The amount of energy, $\mathcal{E}$, that is stored in a charged capacitor is

$$\mathcal{E} = 1/2\ CV^2$$

where $\mathcal{E}$ = energy in joules
C = capacitance in Farads
V = charging voltage

If a 100 μF capacitor is charged to 100 volts it has stored energy equal to

$$\mathcal{E} = 1/2\ CV^2 = \frac{100 \times 10^{-6} \times 100^2}{2} = 1/2$$

$$\mathcal{E} = 0.5\ J$$

The energy stored in a charged capacitor can cause an electrical shock when a person touches the connecting leads. If the capacitor charge voltage is in the area of 50 volts or greater and the stored energy is in the area of 1 joule or more, the shock can be deadly. Charged capacitors, in any case, must be discharged before handling.

CAPACITOR VOLTAGE RATING

While the dielectric constant of the capacitor's insulating material is most important, there is a second critical factor to consider, the dielectric "breakdown voltage." Although the dielectric is an insulator, a very high voltage across the capacitor could tear electrons out of the valence ring of the dielectric atoms. When this happens, the dielectric breaks down and conducts, destroying the capacitor by forming a short circuit between the plates. Because this can happen, it is necessary to pay careful attention to the VOLTAGE RATING of the dielectric. Some voltage ratings of typical dielectric materials are listed in Table 2 in Kilovolts per millimeter.

MATERIAL	BREAKDOWN VOLTAGE kV/mm
Air	3
Glass	20 - 60
Mica	50 - 250
Oil	15
Paper	35
Rubber	16
Plastic	16

TABLE 2 - Dielectric breakdown voltage ratings.

When selecting a capacitor for use in a circuit, the technician must specify the necessary capacitance value and VOLTAGE RATING. The voltage rating is the highest voltage that may be applied across the capacitor without breaking down the dielectric and is called the WORKING VOLTAGE, WV.

In order to increase the working voltage for a capacitor the manufacturer often increases the thickness of the dielectric. This greater thickness increases the plate spacing, d in Figure 5, and results in a reduced capacitance. To raise the capacity back to the desired value the plate area must be increased. Both of these increases, dielectric thickness and plate area, result in an increase in the physical size of the capacitor. Two capacitors with the same capacitance but different voltage ratings will be of different physical sizes.

Capacitor voltage ratings should be at least 20% to 50% greater than the expected voltage in a circuit. A 15 volt rating would be safe for a circuit operated at 10 volts.

CAPACITORS IN PARALLEL

It is frequently necessary to combine capacitors in parallel, series or series-parallel in order to achieve a specific value of capacitance. When combined in any form, two factors are affected; capacitance and voltage rating.

Two capacitors are shown connected in parallel in Figure 6(a). In effect, both of the negatively charged plates are tied together as are both positive plates. The equivalent of this arrangement is shown in Figure 6(b). The effect of connecting capacitors in parallel is to increase the plate area and thus increase the capacitance. The total capacitance can be expressed as

$$C_T = C1 + C2 + C3 + \ldots\ldots\ldots C_N$$

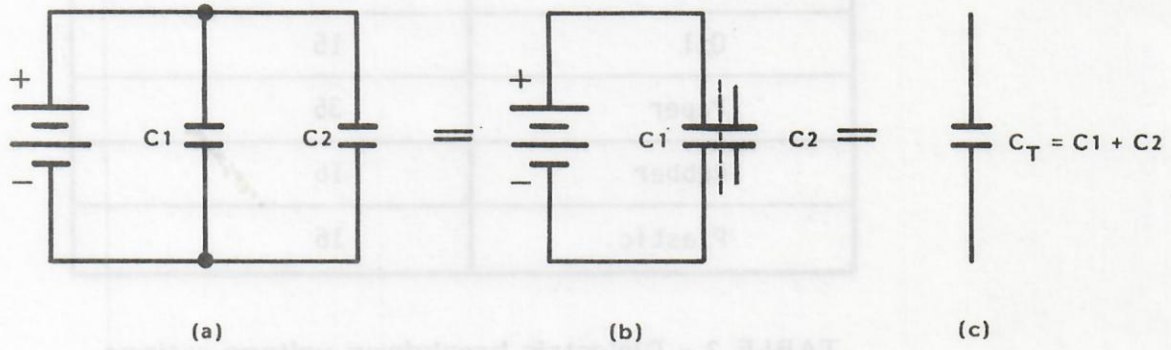


Figure 6 - Capacitors wired in parallel.

Connecting a 50 μF and 22 μF capacitor in parallel produces a capacitance of:

$$C_T = C1 + C2$$

$$= 50 + 22$$

$$\boxed{C_T = 72\ \mu F}$$

CAPACITOR VOLTAGE RATINGS IN PARALLEL

When connected in parallel, the voltage that appears across each capacitor is equal to the source voltage. Each capacitor in the parallel group must have a voltage rating high enough to withstand the source voltage. Shown in Figure 7 are three parallel capacitors, 8 μF, 10 μF and 25 μF for a total of 43 μF. The highest voltage that can be applied to the network is 15 volts, limited by C1.

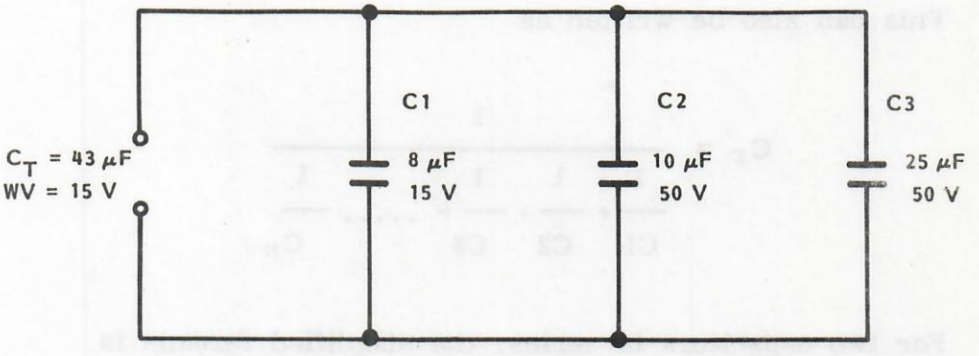


Figure 7 - The WV of the parallel group is 15 volts, that of the lowest rating in the network.

While C2 and C3 can withstand 50 volts, C1 will break down soon after the source voltage excedes 15 volts. When C1 breaks down due to excessive applied voltage it will short out the entire combination.

To summarize, in a parallel capacitor network, the capacitance is additive and the voltage rating is that of the lowest voltage rating in the group.

CAPACITORS IN SERIES

When capacitors are wired in series, the total capacitance is <u>less</u> than the lowest capacitance value in the series circuit. Placing capacitors in series effectively adds the spacing between the plates together and since C varies inversely with d, the total capacitance is lowered. This is illustrated in Figure 8.

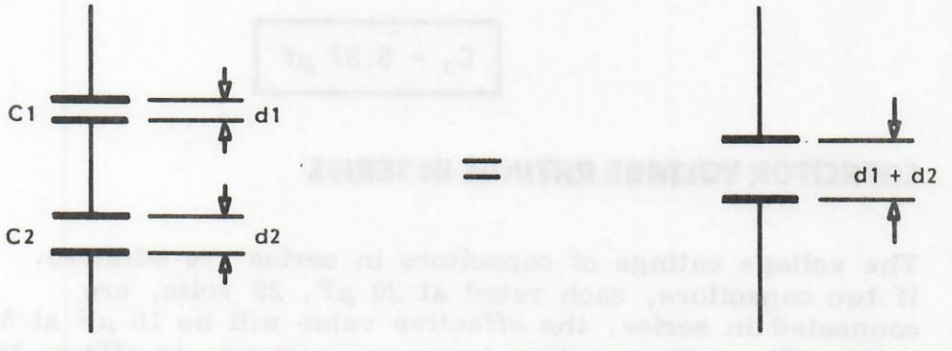


Figure 8 - The effect of wiring capacitors in series.

The total capacitance (C_T) for capacitors in series is given by

$$\frac{1}{C_T} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \ldots\ldots \frac{1}{C_N}$$

This can also be written as

$$C_T = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \ldots\ldots \frac{1}{C_N}}$$

For two capacitors in series, the simplified formula is

$$C_T = \frac{C1 \quad C2}{C1 + C2}$$

You will recognize these formulas for series capacitors as similar to the formulas for parallel resistances.

If two capacitors, 8 μF and 22 μF, are wired in series, the total capacitance will be less then 8 μF. We have

$$C_T = \frac{C1 \quad C2}{C1 + C2}$$

$$= \frac{(8)(22)}{8 + 22} = \frac{176}{30}$$

$$\boxed{C_T = 5.87\ \mu f}$$

CAPACITOR VOLTAGE RATINGS IN SERIES

The voltage ratings of capacitors in series are additive. If two capacitors, each rated at 20 μF, 25 volts, are connected in series, the effective value will be 10 μF at 50 volts. The voltage rating increases because, in effect, the dielectric thickness has doubled.

A problem could exist when two capacitors with different capacities are placed in series. Consider a series circuit consisting of 5 μF and 20 μF capacitors, each with a WV of 25 volts. The total capacity is equal to:

$$C_T = \frac{(C1)(C2)}{C1 + C2}$$

$$= \frac{(5)(20)}{5 + 20} = \frac{100}{25}$$

$$\boxed{C_T = 4\ \mu F}$$

With each capacitor rated at 25 volts a 50 volt source would not appear to be excessive. In practice, however, the 50 volts will not be shared equally between the two capacitors. Most of the 50 volts will appear across the 5 μF capacitor. The circuit is shown in Figure 9.

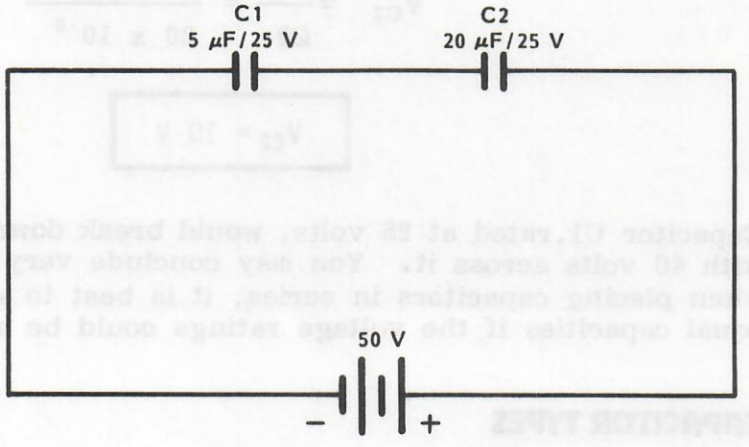


Figure 9 - Two capacitors in series for a total value of 4 μF.

The charge, in coulombs, for the entire circuit is given by

$$Q_T = C_T\ V = 4 \times 10^{-6} \times 50$$

$$\boxed{Q_T = 0.0002 \text{ coulombs or } 0.2 \times 10^{-3} \text{ coulombs}}$$

Once Q_T is known, the charge current for both capacitors is known and they are the same because they are in series.

With Q known, the voltage across each capacitor can be determined from

$$V = \frac{Q}{C}$$

Thus, for C1, we have:

$$V_{C1} = \frac{Q}{C1} = \frac{0.2 \times 10^{-3}}{5 \times 10^{-6}}$$

$$\boxed{V_{C1} = 40 \text{ V}}$$

For C2, the voltage must be 10 volts (50 - 40 = 10) and can be shown as:

$$V_{C2} = \frac{Q}{C2} = \frac{0.2 \times 10^{-3}}{20 \times 10^{-6}}$$

$$\boxed{V_{C2} = 10 \text{ V}}$$

Capacitor C1, rated at 25 volts, would break down very soon with 40 volts across it. You may conclude very quickly that when placing capacitors in series, it is best to work with equal capacities if the voltage ratings could be a problem.

CAPACITOR TYPES

Capacitors are manufactured in a great variety of shapes, sizes and types. They can be roughly divided into two major groups, Fixed capacitors and Variable capacitors. Fixed capacitors will be covered first.

PAPER CAPACITORS

Fixed capacitors are classified by the type of dielectric they use. One of the most common dielectrics is PAPER. Paper capacitors are formed from strips of aluminum foil as the capacitor plates, separated by paper as the dielectric.

The paper is often impregnated with wax or plastic to increase the breakdown voltage rating and increase the dielectric constant. The sandwich of foil and dielectric are formed in long strips and rolled up tightly to conserve space. A second insulator has to be placed in the sandwich to prevent the plates from shorting out when rolled up. This is shown in Figure 10(a). Figure 10(b) illustrates how the capacitor appears after it has been completely rolled, placed in a protective tube and coated with a wax or plastic.

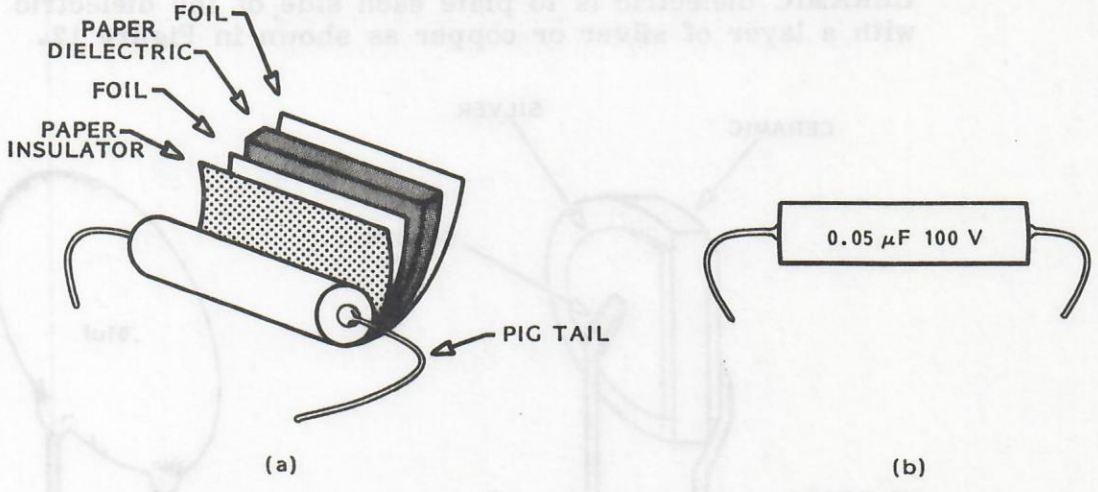


Figure 10(a) - Foil-dielectric combination. (b) - Finished capacitor.

Paper capacitors are available in values that range from 0.0002 μF to 4 μF with working voltages up to 10,000 volts. Some standard working voltages are 10, 15, 25, 100, 200, 400 and 600 volts.

MICA CAPACITORS

MICA capacitors are made of alternate layers of mica and foil as shown in Figure 11(a). They are then enclosed in a moulded case or dipped in molten plastic (also shown in Figure 11).

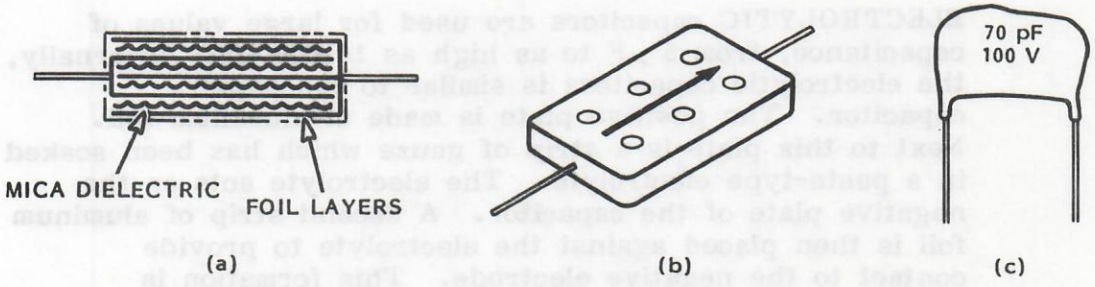


Figure 11(a) - Construction of a mica capacitor. (b) Mica capacitor protected in a plastic case. (c) - Dipped mica capacitor.

Mica capacitors usually have a low capacitance rating, in the picofarad range, but high voltage ratings. Mica has the highest breakdown voltage ratings of all the dielectrics, 50 to 250 kilovolts (kV) per millimeter of thickness.

CERAMIC DISC CAPACITORS

The method of construction used for capacitors with a CERAMIC dielectric is to plate each side of the dielectric with a layer of silver or copper as shown in Figure 12.

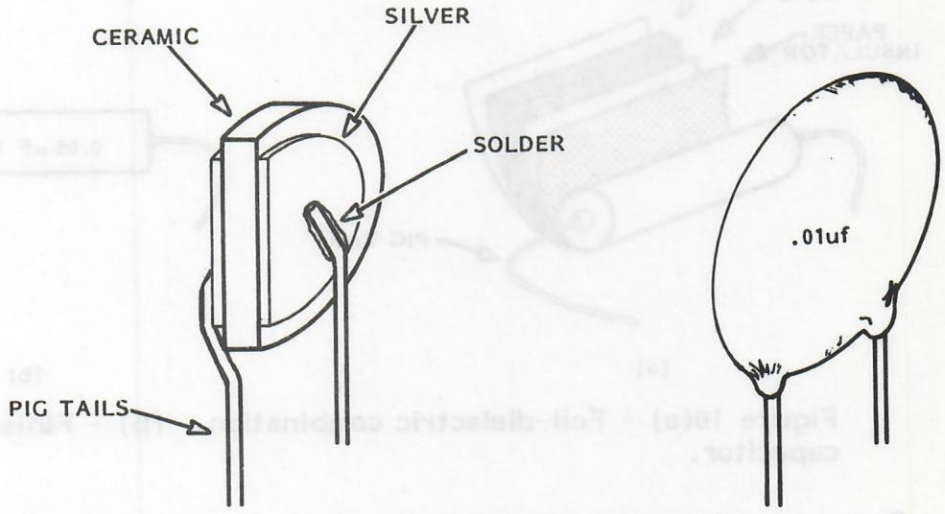


Figure 12 - Construction and appearance of a disc ceramic capacitor.

The dielectric constant of the ceramic can be between 500 to 3000 or more depending upon the type of ceramic mixture used. The high dielectric constants allow large capacitances to be formed in small physical sizes. The capacitor is then coated with an insulating material.

ELECTROLYTIC CAPACITORS

ELECTROLYTIC capacitors are used for large values of capacitance, from 5 μF to as high as 10,000 μF. Internally, the electrolytic capacitors is similar to the paper capacitor. The positive plate is made of aluminum foil. Next to this plate is a strip of gauze which has been soaked in a paste-type electrolyte. The electrolyte acts as the negative plate of the capacitor. A second strip of aluminum foil is then placed against the electrolyte to provide contact to the negative electrode. This formation is illustrated in Figure 13(a).

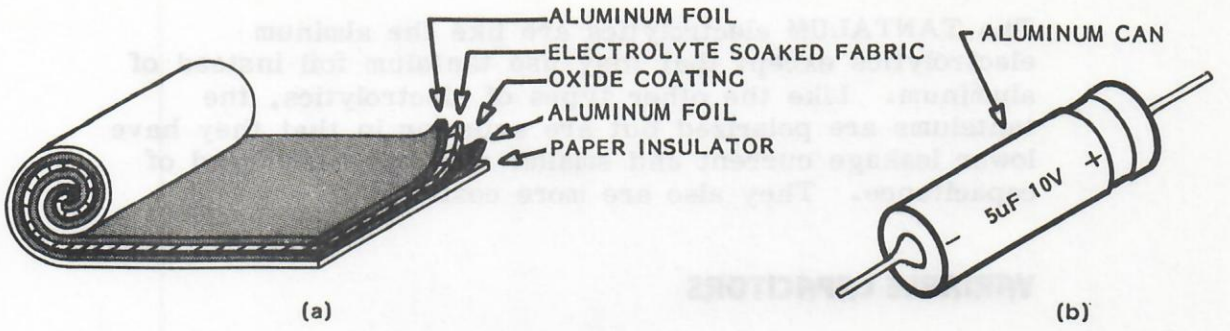


Figure 13(a) - Construction of an electrolytic capacitor.
(b) - A tubular electrolytic.

The foil-electrolyte sandwich is rolled up (with the paper insulator) and inserted in an aluminum can which is one terminal of the capacitor. The electrolytic capacitor is also made in tubular form as shown in (b) of Figure 13.

When voltage is first applied to the capacitor in the manufacturing process, the capacitor is a virtual short circuit. With the application of voltage, an OXIDE coating builds up on the side of the positive plate that is in contact with the electrolyte. The oxide layer that is created is an insulator. The oxide layer is very thin, 0.02 thousands of an inch (0.00002") or less, thus creating a very high capacitance for a small plate area.

Electrolytic capacitors have two disadvantages in that they are POLARIZED and have a small LEAKAGE current flow. The oxide is formed on the positive plate during the manufacturing process. Should the positive plate be accidentally connected to the negative terminal of the voltage source, the thin oxide film dielectric will dissolve and the capacitor will become a conductor, that is, it will be a short circuit. The polarity of an electrolytic is normally clearly marked on its casing to prevent accidental polarity reversal.

LEAKAGE CURRENT

Unlike paper, mica and ceramic capacitors, the electrolytic capacitor will conduct some small current when dc is applied. This is called leakage current and it causes the charge on the capacitor to dissipate quickly even without an external current path.

TANTALUM ELECTROLYTICS

The TANTALUM electrolytics are like the alminum electrolytics except that they use tantalum foil instead of aluminum. Like the other types of electrolytics, the tantalums are polarized but are superior in that they have lower leakage current and smaller size per microfarad of capacitance. They also are more costly.

VARIABLE CAPACITORS

VARIABLE capacitors are used in circuits that require frequent changes in capacitance value such as tuning circuits in radio receivers. The type most often used is the air variable shown in Figure 14(a). A knob is placed on the shaft and as the knob is rotated, the degree of plate mesh is changed thus varying the effective plate area to change capacitance. This type of capacitor normally has an air dielectric and so the maximum capacitance is small, typically 0.000365 μF (365 pF) or less.

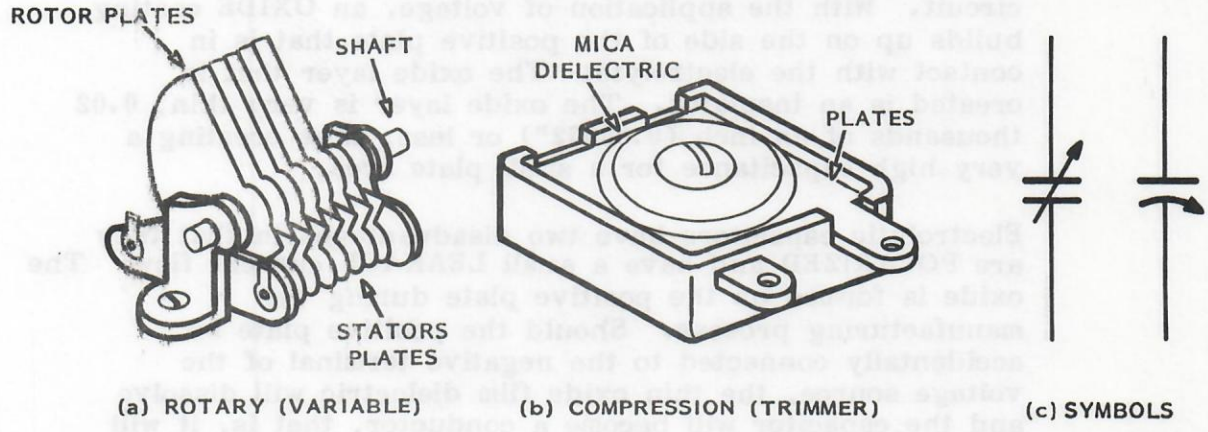


Figure 14(a) - Rotor-stator type variable capacitor.
(b) - Compression trimmer type variable capacitor.
(c) - Variable capacitor symbols.

TRIMMER CAPACITORS

Another type of variable capacitor is the COMPRESSION variable shown in Figure 14(b). It is made up of alternate layers of plates and mica dielectric just as the mica capacitor of Figure 11. In this case, however, there is a screw that can change the compression, changing the spacing and thus changing the capacitance. The compression variable is used for preset adjustments of capacitor values in radios and is often called a TRIMMER capacitor.

CAPACITOR RATINGS AND COLOR CODES

The capacitance and voltage ratings of most capacitors are printed directly on their bodies. Many small capacitors, mica and some ceramic types, have their data recorded on their body by color coded paint dots. The numbers indicated by the colors are the same as those used for the resistor color code but the resulting number is in picofarads. the color code and two 3-dot coded mica capacitors are shown in Figure 15.

	Dots		
Color	1st digit	2nd digit	Multiplier
Black	0	0	x 1
Brown	1	1	x 10
Red	2	2	x 100
Orange	3	3	x 1000
Yellow	4	4	x 10,000
Green	5	5	x 100,000
Blue	6	6	x 1,000,000
Violet	7	7	x 10,000,000
Grey	8	8	x 100,000,000
White	9	9	x 1,000,000,000

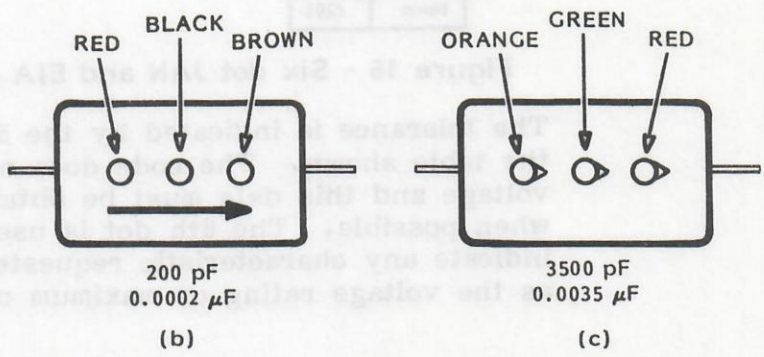


Figure 15(a) - Color code. (b) - Color coding for a 200 pF mica capacitor. (c) - Arrow is formed around color dots.

The 3-dot coding system shown in Figure 15 is used for mica capacitors that have a working voltage of 500 volts and a ±20% tolerance. The first and second color dots represent the significant digits and the third color, the multiplier. The code must be read in the direction of the arrow on the capacitor body or a wrong capacitance reading will result. The arrow is often formed as part of the dots as shown in Figure 15(c).

SIX DOT CODES

The 6-dot color code is used by the Electronic Industries Association (EIA) and the Joint Army Navy group (JAN) and is shown in Figure 16. If the first dot of the color code shown is white, the capacitor meets EIA standards. A black dot in this position indicates that the capacitor meets the higher JAN standards. The next three colors represent the first and second digits and the multiplier to indicate the capacitance in $\mu\mu$F.

Color	% Tol.
Black	
Brown	
Red	±2%
Orange	±3%
Yellow	
Green	±5%
Blue	
Violet	
Grey	
White	
Gold	±5%
Silver	±10%
None	±20%

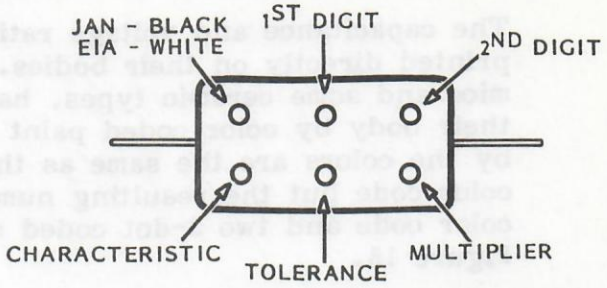
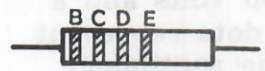


Figure 16 - Six dot JAN and EIA color code and Tolerance table.

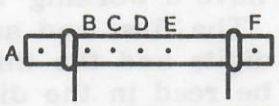
The tolerance is indicated by the 5th dot in accordance to the table shown. The code does not indicate the working voltage and this data must be obtained from the manufacturer when possible. The 6th dot is used by the manufacturer to indicate any characteristic requested by the purchaser such as the voltage rating or maximum operating temperature.

CERAMIC CAPACITOR COLOR CODES

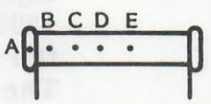
Ceramic capacitors are made in both disc and tubular form, as shown in Figure 17, and use a 3-dot, 5-dot and 6-dot color code.



AXIAL LEAD CERAMIC

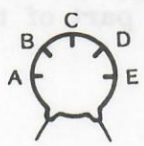


6 DOT RADIAL LEAD



5 DOT RADIAL LEAD

3 DOT CERAMIC DISC



5 DOT CERAMIC DISC

KEY:

A = TEMP COEFF
B = 1ST DIGIT
C = 2ND DIGIT
D = MULTIPLIER
E = TOLERANCE
F = VOLTAGE RATING

Color	Capacitance			Tolerance		Temperature coefficient PPM/C°	Voltage rating, volts
	1st digit	2nd digit	Multiplier	Above 10μμf	10μμf and less		
Black	0	0	1	±20%	±2μμf	0	
Brown	1	1	10	±1%		-30	150
Red	2	2	100	±2%		-80	
Orange	3	3	1000			-150	350
Yellow	4	4	10,000			-220	
Green	5	5		±5%	±0.5μμf	-330	500
Blue	6	6				-470	
Violet	7	7				-750	
Grey	8	8	0.01		±0.25μμf	+30	
White	9	9	0.1	±10%	±1.0μμf	+120 to -750 EIA	
Silver						+500 to -330 JAN	
Gold							

Figure 17 - Color code and key for ceramic capacitors.

Different types of ceramic capacitors use different color codes as shown in Figure 17. Note that:

1. If a 4-dot code is used, dot A, Temperature Coefficient, is omitted.

2. There are two columns for tolerance rating in Figure 17, one for capacitors above 10 $\mu\mu$F and the other for below 10 $\mu\mu$F. Observe the different methods of rating each type, one by percentage and the other by capacitance deviation.

3. Since ceramic capacitors are often used in circuits where heat generation must be taken into account, the capacitor Temperature Coefficient is listed. This is a measure of how much and in which direction the capacitance will change with heat. It is rated parts per million per degree centigrade (PPM/C°).

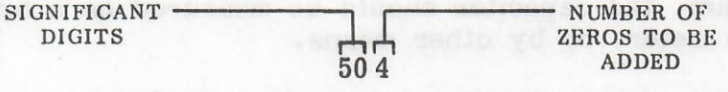
As shown in Figure 17, axial lead ceramics use a 4-dot color code. The voltage rating is not coded and is 500 volts.

Radial lead ceramics use the 5 or 6-dot code as shown. The 5-dot code does not indicate the voltage rating which is always 600 volts. The 6-dot coded ceramics can be 150, 350 or 500 volts as indicated by dot F.

The standard color code for the disc ceramics is also shown in Figure 17. The three dot code is read from left to right with the leads pointed up while the 6-dot code must be read with the leads pointed down. Both the 3-dot and 6-dot coded disc ceramic capacitors have 500 volt ratings. The majority of the disc ceramic capacitors do not use a color code but simply have the data printed on the body.

MARKED VALUE ON CAPACITOR

One of the more recent methods of indicating the value of a disc capacitor is to print a three digit number on the body as shown in Figure 18. The first two digits are the significant digits and the third digit represents the number of zeros to be added. The three digit number is the value in pF. The first example in Figure 18 is that of a disc capacitor marked 504. This translates as:



= 50 0000 pF

To convert to μF, it is necessary only to move the decimal point 6 places to the left as shown below. Moving the decimal point in steps of three, we have:

.500.000. = 0.5 μF

Several additional examples are shown in Figure 18.

CAPACITOR MARKING	CAPACITOR VALUE	MARKED VALUE IS IN pF	CONVERT pF to μF BY MOVING 6 PLACES LEFT
	0.5 μF	50 0000 (4)	0.500.000. μF
	0.1 μF	10 0000 (4)	0.100.000. μF
	0.01 μF	10 000 (3)	0.010.000. μF
	0.001 μF	10 00 (2)	0.001.000. μF
	150 pF	150 K (see note below)	0.000.150. μF
	22 pF	22	0.000.022. μF

Figure 18 - Three number disc capacitor code.

Notes for Figure 18:

A capacitor marked 150 in the above code could be interpreted as 15 pF. As noted earlier, however, under Capacitor Ratings and Color Codes, capacitor values are often printed directly on the capacitor body. The 150 marking, as shown, would usually indicate 150 pF corresponding to this earlier practice. Recent capacitors of 150 pF would be marked as 151. To be certain, the capacitor should be measured on a bridge, capacitance meter, or by other means.

The tolerance ratings for the code in Figure 18 are:

J = ± 5% K = ± 10% M = ± 20 %

CONCLUSIONS

We have learned from this experiment that:

A capacitor is made up of two conductors (plates) separated by a dielectric.

The capacitor can store energy.

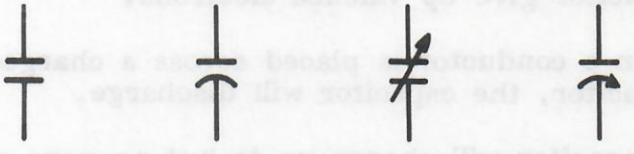
The energy a capacitor is able to store is directly proportional to the plate area and inversely proportional to dielectric thickness.

Capacitors are rated in farads but the farad is too large a unit so the μF and $\mu\mu$F (pF) are used.

A capacitance of 1 farad exists when 1 ampere of charging current causes a voltage rise of 1 volt in 1 second.

The capacitor charge, in coulombs, is calculated from $Q = CV$.

The capacitor symbols are:



The energy, in joules, stored in a capacitor is determined from $\mathcal{E} = 1/2\ CV^2$.

Large capacitance values charged by voltages over 50 volts can store lethal amounts of energy.

Capacitors have Working Voltage ratings, determined by the dielectric material and dielectric thickness.

Capacitors wired in parallel increase the effective plate area and so increase effective capacitance.

Capacitors wired in series have an effective capacitance that is less than the lowest value capacitor in the series network.

Capacitors may be divided into two major groups, fixed and variable.

Fixed capacitors are classified by their dielectric materials such as mica, paper, ceramic and so on.

Electrolytic capacitors are used for large values, of capacitance because their dielectric, an oxide coating, is so thin.

Electrolytics use aluminum or tantalum to form the plates of the capacitor.

ASSIGNMENT

Answer the following True-False questions.

1. A capacitor is formed from two insulators separated by a conductor. ____

2. The capacitor, when charging, has a high current flow initially and then the current drops in value until the capacitor is fully charged at which time the current is zero. ____

3. When the charging voltage is removed from a capacitor, it discharges immediately. ____

4. As electrons enter one plate of a capacitor they force electrons off the opposing plate. ____

5. The dielectric of a capacitor acts as an insulator and also stores energy. ____

6. The atoms of a dielectric, in a charged capacitor give up valence electrons. ____

7. When a conductor is placed across a charged capacitor, the capacitor will discharge. ____

8. A capacitor will charge up to but no more or less than the source voltage. ____

9. The farad is not a practical unit so the metric prefixes kilo and mega must be used with it. ____

10. A capacitor of 1 farad may be defined as one which when charged by one ampere for one second will rise one volt. ____

11. The charge on a capacitor, in coulombs, is expressed as $C = Q/V$. ____

12. As the plate area of a capacitor is increased, the capacity increases. ____

13. The greater the distance separating the capacitor plates, the less the capacity. ____

14. The lower the dielectric constant, the greater the capacitance it will produce. ____

15. The energy, $\mathcal{E}$, stored in a capacitor is determined by the capacity and the charging voltage. ____

16. The greater the charging voltage and the smaller the capacitance, the greater the energy stored (in joules). ____

17. The voltage rating of a capacitor is determined by the dielectric material used and the dielectric thickness. ____

18. If the dielectric thickness is increased to raise the WV, the capacitance will decrease unless the plate area is increased to compensate. ____

19. The capacitance of capacitors wired in parallel are additive. ____

20. The voltage rating of capacitors wired in parallel are additive. ____

21. Capacitors wired in series develop a reduced effective capacitance but a higher voltage rating. ____

Perform the following calculations.

22. Determine the capacitance value of a capacitor that has a charging current of 1 mA, a delta v of 2 volts and a delta t of 0.1 seconds.

23. a. Determine the charge, in coulombs, on a 20 μF capacitor connected across a 100 volt source.

b. Determine the actual number of electrons stored in the negative plate.

24. Calculate the capacitance developed by a pair of plates that have an area of 50 square inches, that are separated 0.02 inches by a dielectric with a constant of 40.

25. a. Three capacitors are wired in parallel. They are 50 μF/10 V; 22 μF/25 V; 12 μF/50 V. Calculate the capacitance of the network and the maximum voltage it can withstand.

b. Two capacitors are wired in series. They are 50 μF each, both rated at 10 volts. Calculate the total capacitance and WV.

Answer the following multiple choice questions.

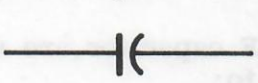
26. Electrostatic lines of force are said to flow from:

a. positive to negative.
b. negative to positive.
c. north to south.
d. south to north.

27. The symbol for a capacitor is:

a.

c.

b. 

d. all of the above.

28. A capacitor can store energy in its:

a. positive plate only.
b. negative plate only.
c. dielectric.
d. none of the above.

29. When a capacitor is charged:

a. each plate has an equal number of electrons.
b. one plate has an excess of electrons while the other plate has an excess of neutrons.
c. the dielectric atom's electron orbits are distorted.
d. all of the above.

30. Most electrolytic capacitors are:

a. polarized.
b. not made in variable form.
c. made using aluminum plates.
d. all of the above.

31. A 5 μF capacitor is equal to:

a. 5,000 pF.
b. 50,000 pF.
c. 5,000,000 pF.
d. none of the above.

32. Capacity increases when the capacitor:

a. plates are moved further apart.
b. plates are moved closer together.
c. dielectric constant is decreased.
d. dielectric is made thicker.

33. A capacitor is designed with a mica dielectric (k=3) with a thickness of 0.0001 inches. If the mica is replaced with the same thickness plastic, Neoprene, (k=4) the effect will be to:

a. reduce the capacitance and voltage rating.
b. reduce the capacitance and increase voltage rating.
c. increase capacitance but reduce voltage rating.
d. increase the capacitance and voltage rating.

34. A 50 μF capacitor and a 100 μF capacitor are wired in series. The capacitance will be equal to:

a. 33.3 μF.
b. 150 μF.
c. 333.3 μF.
d. none of the above.

35. A 50 μF and 100 μF capacitor are wired in series across 150 volts. The voltage will divide between the capacitors with:

a. equal values.
b. more across the 50 μF and less across the 100 μF.
c. more across the 100 μF and less across the 50 μF.
d. none of the above.

36. The total capacitance and working voltage for the network shown in Figure 18 is:

a. 90 μF/30 V.
b. 30 μF/70 V.
c. 20 μF/80 V.
d. 10 μF/30 V.

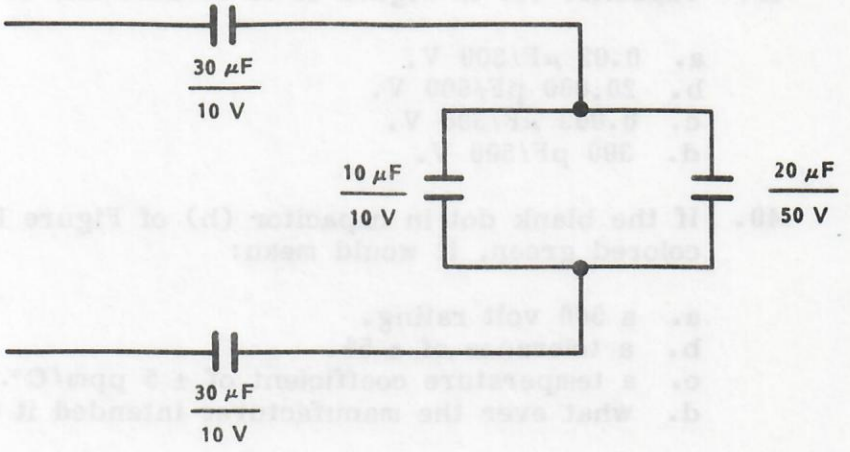


Figure 18.

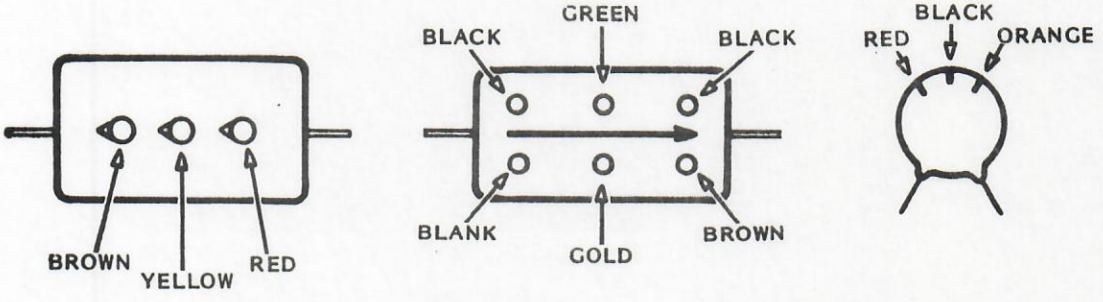


Figure 19 - Refers to questions 37 to 40.

37. A mica capacitor is color coded as shown in (a) of Figure 19. Its value is:

a. 240 pF.
b. 240 μF.
c. 1400 pF.
d. 0.0014 μF.

38. The capacitor shown in (b) of Figure 19 is:

    a. in the JAN code.
    b. in the EIA code.
    c. ± 20% tolerance.
    d. rated at 300 volts.

39. Capacitor (c) in Figure 19 is ceramic and is rated at:

    a. 0.02 μF/300 V.
    b. 20,000 pF/600 V.
    c. 0.003 μF/500 V.
    d. 300 pF/500 V.

40. If the blank dot in capacitor (b) of Figure 19 was colored green, it would mean:

    a. a 500 volt rating.
    b. a tolerance of ± 5%.
    c. a temperature coefficient of ± 5 ppm/C°.
    d. what ever the manufacturer intended it to mean.

KEY TERMS

1. CAPACITANCE

   The property of being able to store electrical charges and is equal to the ratio of the charges stored to the voltage across the capacitor plates ($C = Q/V$).

2. CAPACITOR

   A device consisting of two conductors separated by an insulator that can store electrical energy.

3. CERAMIC CAPACITOR

   A capacitor that makes use of ceramic as the dielectric.

4. CHARGE

   The electrical energy, Q, stored in a capacitor; $Q = CV$.

5. COLOR CODE

   A system of colored paint dots used to code some types of capacitors. The code is read like the resistor color code with the resulting number in picofarads.

6. COMPRESSION TRIMMER

   A variable capacitor in which the spacing between the plates is changed by compression to vary the effective capacity.

7. COULOMB

   One coulomb is the charge carried by 6.25×10^{18} electrons.

8. DELTA

   The Greek letter, delta, means change. Thus Δi means a change in i which represents current.

9. DIELECTRIC

   An insulator placed between two conductors to form a capacitor. Typical dielectrics are air, paper, mica, ceramic, mylar and many others.

10. DISCHARGE

    The release of energy stored in a capacitor when a complete circuit is connected across the capacitor terminals.

11. ELECTROLYTIC CAPACITOR

A capacitor whose dielectric is deposited on the anode through electrolysis. An electrolyte must be present for the action to occur.

12. ELECTRIC FIELD

The field set up between the charged plates of a capacitor. The lines of force flow from the positive charge to the negative charge.

13. ENERGY

The ability to perform work. Energy, $\mathcal{E}$, is stored in a charged capacitor.

14. FARAD

The unit of capacitance. A farad produces a 1 volt difference of potential when charged by 1 coulomb.

15. JOULE

The unit of energy. The work accomplished by a force of 1 newton over a distance of 1 meter. A joule is equal to 1 Newton-Meter.

16. LEYDEN JAR

The original capacitor invented in the town of Leyden, Holland in or about 1715, by Pieter Van Musschenbroek.

17. MICA CAPACITOR

A capacitor that uses mica as the dielectric. It has a high breakdown voltage but a relatively low dielectric constant and so is used for small value capacitors.

18. MICROFARAD

One millionth of a farad or F x 10^{-6} abbreviated as mF or μF.

19. OXIDE

The insulating layer formed on the aluminum anode of the electrolytic capacitor by the chemical action of the electrolyte when current flows through it.

20. PAPER CAPACITOR

A capacitor that uses treated paper as a dielectric.

21. PICOFARADS

One billionth of a farad or F x 10^{-12}. Abbreviated as pF and also known as the micromicrofarad, mmf or $\mu\mu$F.

22. TANTALUM

An electrolytic capacitor that uses tantalum for the plates rather than aluminum.

23. VOLTAGE RATING

The maximum voltage to which an electronic or electrical component should be subjected to.

24. WORKING VOLTAGE

The same as Voltage Rating, 23, above.

Capacitor Action 3

OBJECTIVES

When you finish this experiment, you will be able to:

1. Describe the construction of various types of capacitors.
2. Recognize and convert from unit to unit, capacitor dimensions in farads, microfarads and picofarads.
3. Calculate the charge, in coulombs, on a capacitor.
4. Test a capacitor for storage of a charge.
5. Read capacitor color codes.
6. Identify various types of capacitors.
7. Test capacitors for shorts, opens or leakage using an ohmmeter.
8. Measure the time required to discharge a capacitor through a resistance.

ADDITIONAL EQUIPMENT

a. Analog Ohmmeter, VOM (Optional)
b. Capacitor Card or selection of capacitors (Optional)

DESCRIPTION

Capacitor construction, operation and types were described earlier in Information Sheet 3, Capacitors, and should be read before performing this experiment. This experiment demonstrates charging and discharging action of a capacitor, the ability of a capacitor to "block" dc but "pass" ac, identification of different types of capacitors, reading capacitor color codes and capacitor testing with an ohmmeter.

CAPACITOR CHARGING ACTION

A capacitor consists of two conductors (metal plates) separated by an insulator called a "dielectric." Electron charges accumulate on the capacitor as shown in Figure 1.

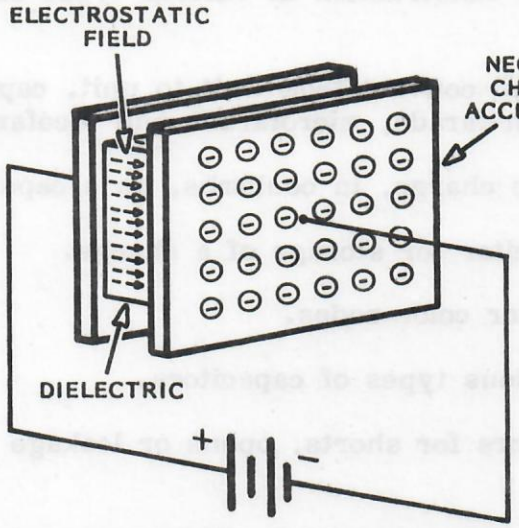


Figure 1 - Basic construction of a capacitor showing charge accumulation and electrostatic field.

The capacitor rating in μF or pF is an indication of how great an electron charge can be stored for a given voltage. The formula is

$$Q = CV$$

where Q = charge in coulombs
C = capacitance in farads
V = charging voltage in volts

ELECTRON CHARGE

In this experiment you will charge a 100 μF capacitor to 18 volts (between -V2 and +V2). The accumulated charge is given by

$$Q = CV$$

$$= (100 \times 10^{-6})(18)$$

$$= 18 \times 10^{-4} \text{ coulombs}$$

CHARGE Q = 0.0018 coulombs

Because each coulomb is equal to 6.25×10^{18} electrons, the number of electrons (Ne) held in the capacitor charge is given by

$$Ne = \text{Number of coulombs} \times 6.25 \times 10^{18}$$

$$= (0.0018)(6.25 \times 10^{18})$$

$$\boxed{\text{ELECTRONS } Ne = 11.25 \times 10^{15}}$$

or the number is 11,250 trillion electrons.

Thus, when a 100 μF capacitor is charged to 18 volts it is holding 11.25×10^{15} electrons on its negative plate and the same number of electrons is missing from the positive plate.

CAPACITOR DISCHARGING ACTION

The energy stored in a capacitor can do work when released. This is shown by causing the capacitor discharge to energize Lamp 1 on the trainer panel. The charge on the plates equalize by flowing through the external lamp circuit as shown in Figure 2. The lamp will glow for a moment until the capacitor is discharged.

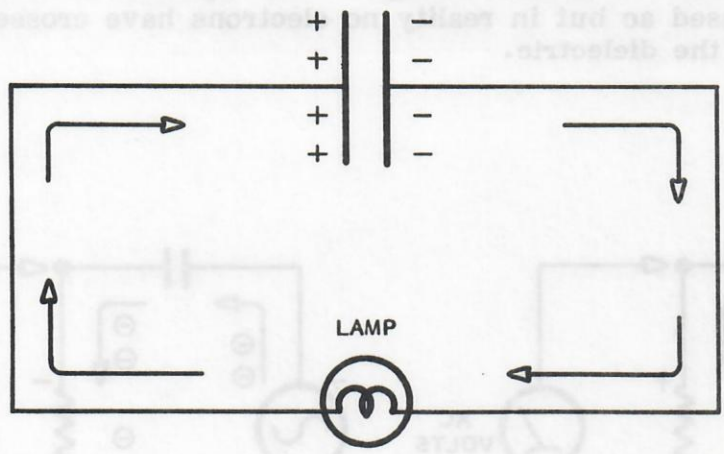


Figure 2 - Charged capacitor forces current through the lamp.

CAPACITOR BLOCKING ACTION ON DC AND AC

It has been established that electrons do not pass through dielectric of a capacitor. When connected into a dc circuit capacitors will charge as shown in Figure 3 and the charging current will drop to zero after a given time resulting in no voltage drop across R1.

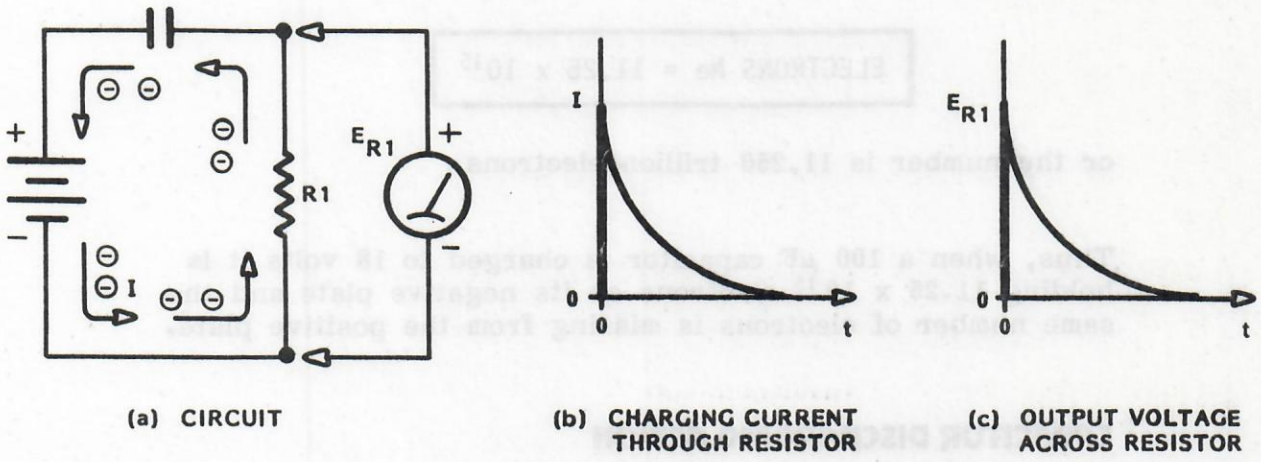


Figure 3 - DC voltage applied through a capacitor.

When ac is applied to a capacitor as shown in Figure 4, the capacitor plates charge to one polarity during the first half cycle. During the next half cycle, the plates discharge and recharge to the new polarity. An ac meter placed across R1 will read a constant voltage. The capacitor is said to have passed ac but in reality no electrons have crossed through the dielectric.

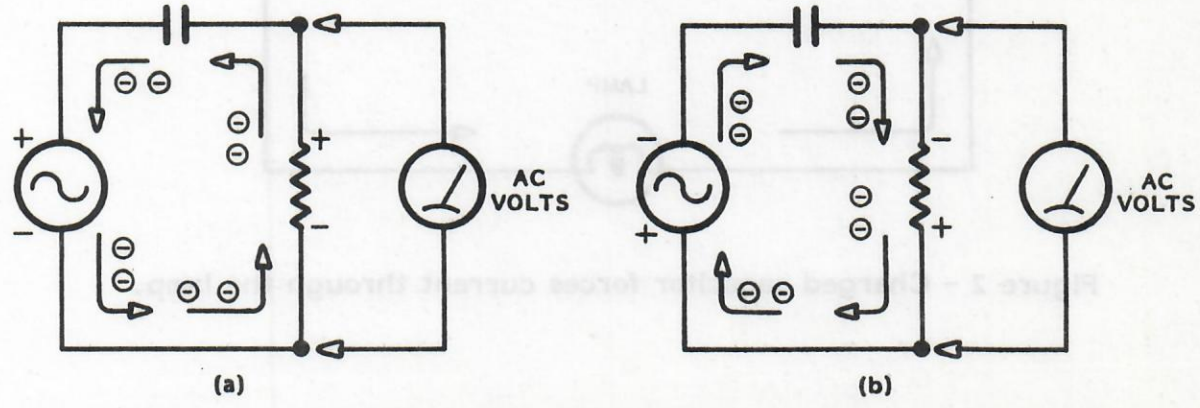


Figure 4 - Ac in a capacitive circuit.

OPPOSITION TO AC

It was stated earlier that a capacitor passes ac but blocks dc and while true, this is an over-simplification. A capacitor will pass ac in the manner described earlier if the frequency of ac is high enough and the capacitance is large enough.

Recall that as the capacitor charges with electrons (Q) it builds up a voltage that is determined by the charge (electrons) and the capacitance where $E = Q/C$. The smaller the capacitance, the larger the voltage developed for a given number of electrons. For a small capacitance value, the voltage builds up quickly and the current flow soon stops.

This opposition to the flow of current is the ac equivalent of resistance and is due to the capacitor's REACTION to the charging current and is thus called REACTANCE which is designated by the letter X. To further identify it as CAPACITIVE REACTANCE, the subscript C is used as X_C. Reactance, like resistance is measured in ohms.

For a large value capacitor, the current flows for a long time and long before the capacitor is fully charged, the input ac voltage reverses direction. The current then flows in the opposite direction to discharge and recharge the capacitor to the new polarity. With a large value capacitor, the current flow can be high and not stop for any part of the ac cycle. Thus, for large capacitor values, in relation to the ac frequency, the CAPACITIVE REACTANCE is low and the current high.

For small values of capacitance, the charging is faster and smaller currents flow. This indicates a large CAPACITIVE REACTANCE for small values of capacitance.

TESTING CAPACITORS

There are several faults that capacitors are subject to. If the dielectric breaks down completely, the capacitor shorts. If the dielectric suffers a partial breakdown, the capacitor becomes "leaky" and develops an internal resistance. Capacitors may also "open" circuit to produce zero capacitance or they can suffer a partial loss of capacitance. All of these types of failures can be determined by using an ohmmeter.

When testing a capacitor with an ohmmeter, the capacitor should be removed from the circuit (at least one end disconnected) and the capacitor should first be discharged. The testing procedure is shown below in Figure 5.

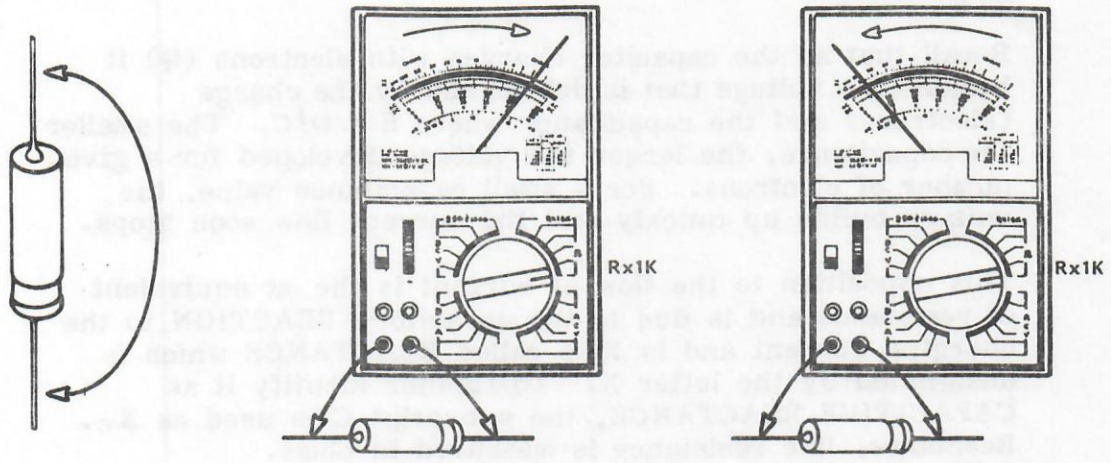


Figure 5 - Ohmmeter testing of a capacitor.

After discharging the capacitor, the ohmmeter leads are connected across the capacitor as shown in (b). The high initial charging current will move the pointer to the right as shown. For very large capacitance values (100 or more μF) the pointer will reach zero ohms. As shown in (c), the current flow reduces gradually indicating normal charging action. The meter pointer will come to rest close to or at infinity.

If the capacitor is shorted, the meter pointer will swing to zero and remain there.

If the capacitor is leaky the meter pointer will swing to zero, start up-scale but stop somewhere short of infinity.

If the capacitor is open, the meter pointer will fail to swing toward zero ohms.

If the capacitor has lost capacity, the meter pointer will swing toward zero but not as far or as fast as it should.

In this experiment you will charge a capacitor and use the charge to energize a lamp. You will observe the effects on the charge of increased (parallel) and decrease (series) capacitance.

PROCEDURE

1. Connect two wires to one of the 100 μF capacitors as shown in Figure 6 and hold the loose ends of the leads by the plastic insulators.

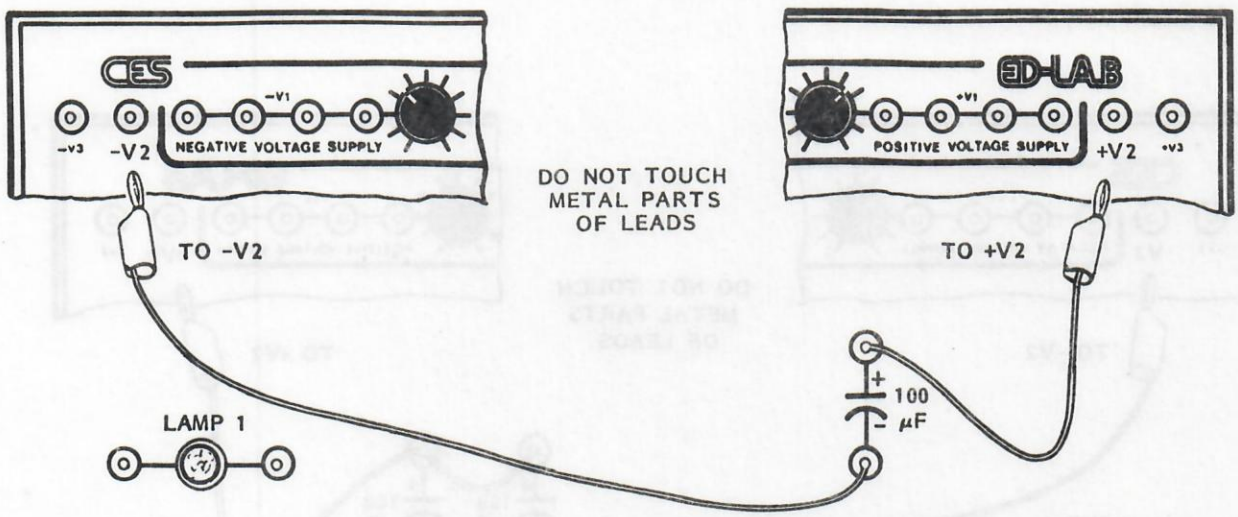


Figure 6 - Capacitor charge storage EXPERIMENT.

3.1 CAPACITOR CHARGE STORAGE

2. The 100 μF capacitor is "polarized" which means that the end marked + is to be connected to the +V2 terminal.

   Momentarily, connect the two leads to +V2 and -V2. Remember, this places a charge on the capacitor of 0.0018 coulombs or 11.25×10^{15} electrons (11,250 trillion electrons).

3. While watching Lamp 1 carefully, so as not to miss the flash, touch the two plugs to the Lamp 1 jacks.

   What did you see and why?_____

3.2 CAPACITORS IN PARALLEL

4. Connect the two 100 μF capacitors in parallel as shown in Figure 7 and momentarily connect them to the -V2 and +V2 jacks.

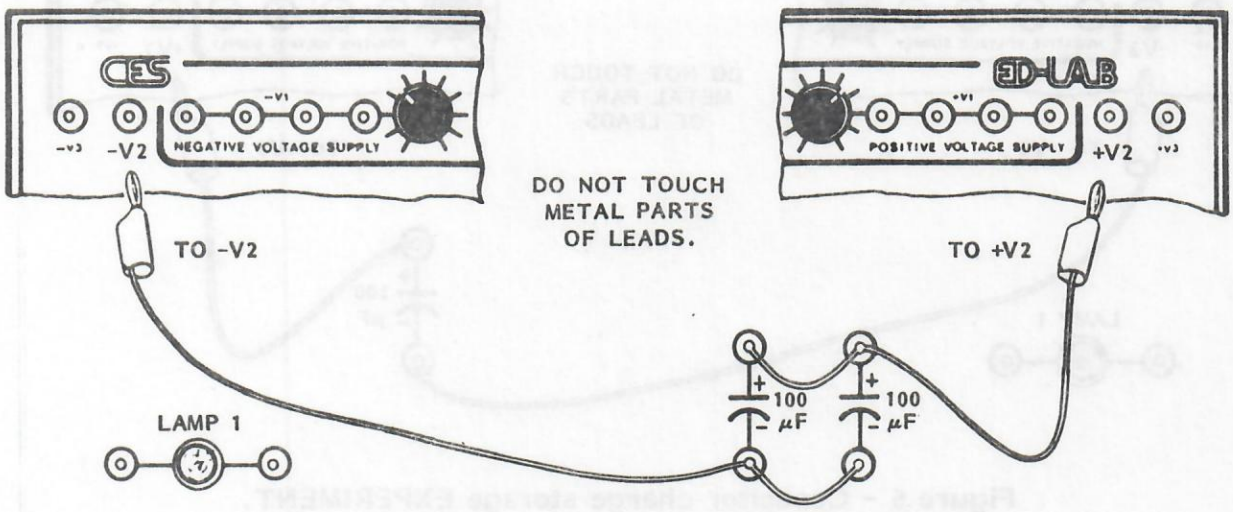


Figure 7 - Charging paralleled capacitors; EXPERIMENT.

5. While watching Lamp 1 carefully so as not to miss the flash, touch the two plugs to the Lamp 1 jacks.

What did you see and why? _____

_____

_____

_____

What is the effective capacitance of the two 100 μF units when in parallel? _____

3.3 CAPACITORS IN SERIES

6. Rewire the two capacitors so that they are in series as shown in Figure 8.

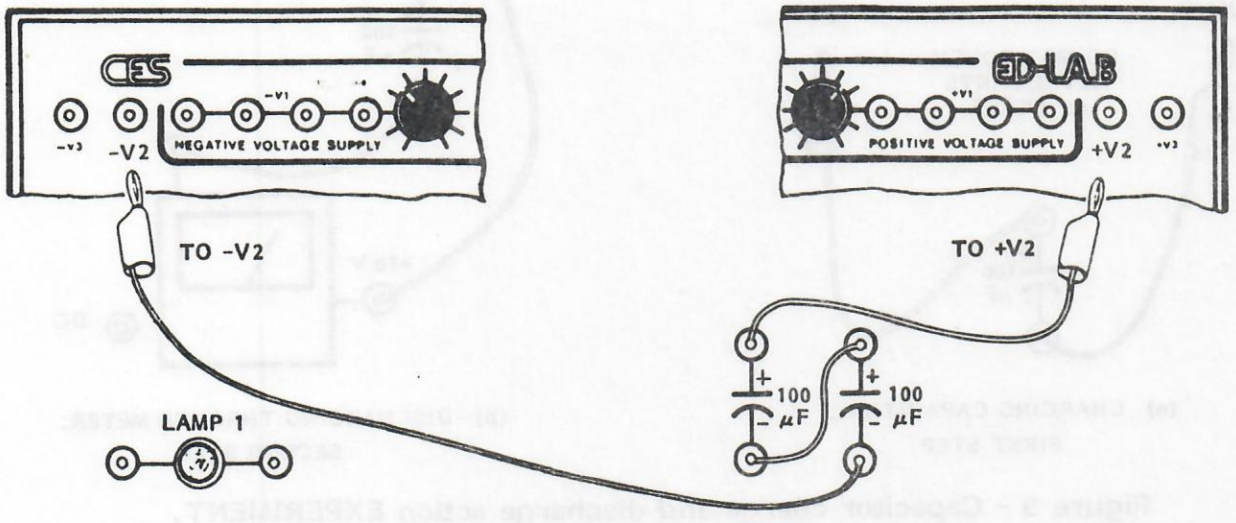


Figure 8 - Capacitors wired in series; EXPERIMENT.

7. Charge the series capacitors from -V2 to +V2 as done earlier. Remove them from -V2 and +V2 and connect them across Lamp 1.

What did you see Lamp 1 do and why? _____

_____

_____

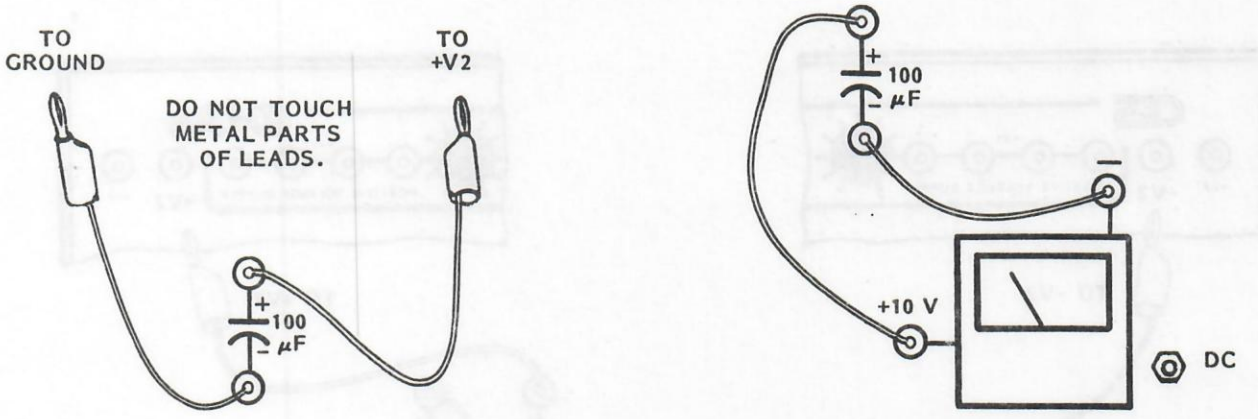
_____

What is the effective capacitance of the two 100 μF capacitors in series?

_____

3.4 METER RESISTANCE DISCHARGE

8. Charge a single 100 μF capacitor to 9 volts by connecting it to +V2 and ground as shown in Figure 9(a). Be sure not to touch the metal parts of the plugs.



(a) CHARGING CAPACITOR. FIRST STEP

(b) DISCHARGING THROUGH METER. SECOND STEP

Figure 9 - Capacitor charge and discharge action EXPERIMENT.

9. Set the meter switch to DC as shown in Figure 9(b).

Connect the two wires from the charged capacitor to the meter as shown in (b), observing the polarity.

Watch the meter pointer movement. What occurs? _____

_____

_____

_____

3.5 CAPACITOR CHARGE CALCULATION

10. The charge that was stored in the 100 μF capacitor is given by the equation

$$Q = CV$$

where Q = charge in coulombs
C = capacitance in farads
V = charging voltage in volts

In step 8 of the experiment, we used 9 volts and a capacitance of 100 μF.

Calculate the charge on this capacitor.

$$Q = CV$$

$$Q = (100 \times 10^{-6})\ (9)$$

CHARGE STORED IN CAPACITOR IN STEP 8	Q = _____ COULOMBS

3.6 ENERGY STORAGE CALCULATION

11. The energy stored in a capacitor is given by the equation

$$\mathcal{E} = \frac{CV^2}{2}$$

where $\mathcal{E}$ = energy in joules
C = capacitance in farads
V = charging voltage in volts

In step 8 of the experiment, we used 9 volts and a capacitance of 100 μF.

Calculate the energy stored in this capacitor.

$$\mathcal{E} = \frac{CV^2}{2}$$

$$\mathcal{E} = \frac{(\quad)(\quad^2)}{2}$$

ENERGY STORED IN CAPACITOR IN STEP 8	$\mathcal{E}$ = _____ joules

Has the capacitor stored sufficient energy to create a shock hazard?

_____

3.7 DISCHARGE TIME

12. Charge the 100 μF capacitor to 9 volts again as shown earlier in Figure 9(a).

13. Now, using a watch or counting the time in seconds, you will determine the number of seconds that it takes the capacitor to discharge from 9 volts to 3 1/3 volts.

    Look at your watch and at the meter and connect the leads to the meter +10 and - inputs again as shown in Figure 9(b), earlier.

    Enter the discharge time below.

TIME (9 V to 3.3 V) = _____ SECONDS

3.8 TIME CONSTANT (OPTIONAL)

14. The capacitor discharge circuit is the internal resistance of the voltmeter set at the 10 volt scale. Since the meter is 20,000 ohms per volt, the total resistance is 20 K x 10 or 200 K. The discharge circuit is shown in Figure 10.

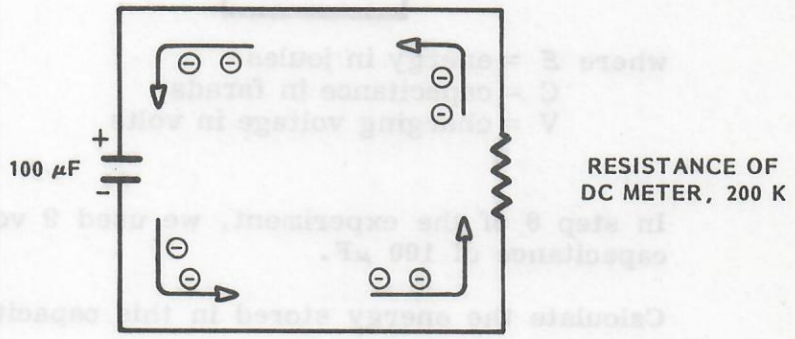


Figure 10 - Actual discharge circuit of the capacitor through the meter.

15. The subject of TIME CONSTANTS for a capacitor and resistor is covered in a later experiment for charging as well as discharge times. In that experiment, one of the facts stated will be that the Time Constant (T) is equal to the product of R and C. Thus:

$$T = R \cdot C$$

where T = time in seconds
R = resistance in ohms
C = capacitance in farads.

The Time Constant for the circuit of Figure 10 is

$$T = R \cdot C$$

$$= 200 \times 10^{3} \times 100 \times 10^{-6}$$

$$\boxed{T = 20 \text{ SECONDS}}$$

Is the time that you measured earlier in step 13 close to 20 seconds?

As discussed later, the time constant of the RC network is the time required for the voltage to discharge 63% of its full charge so that only 37% of the voltage remains. For the 100 μF and the 200 K resistance the time constant is 20 seconds, the time it took to drop from 9 volts to 37% of 9 volts or 3 1/3 volts.

Time constants will not be discussed any further now but will be covered in depth in a later experiment.

3.9 CHARGE AND VOLTAGE RETENTION

A capacitor with a perfect dielectric will hold a charge for an indefinite period. Since no insulator is perfect, particularly in an electrolytic capacitor which has leakage, the charge will gradually dissipate but over a long period of time.

16. Recharge the 100 μF capacitor from ground to +V2 as in Figure 9(a).

17. Look carefully at the meter to be able to determine the initial voltage reading at the exact moment the wires are connected to the meter as designated on the following page.

Connect the two wires to the meter and record the initial voltage reading.

CAPACITOR VOLTAGE READING	_____ V

Although the supply voltage is 9 volts, there will be slight discharge through the meter before the meter pointer moves fully up scale and the reading will be slightly less than 9 volts.

18. Recharge the 100 μF capacitor across ground and +V2 and then remove all wires, even from the capacitor, but remember which 100 μF capacitor you charged.

100 μF CAPACITOR CHARGED LEFT ☐ RIGHT ☐

19. Wait more than 1 minute.

Record the time waited.

TIME WAITED = _____

20. Again connect the two wires from the capacitor to the meter and record the initial voltage reading.

DELAYED VOLTAGE READING	_____ V

Has the capacitor held the voltage charge for over a minute?

_____

How long do you think this electrolytic will hold a charge?

_____

Does this suggest a safety hazard and how can the hazard be corrected?

_____

_____

_____

3.10 BLOCKING DC AND PASSING AC

21. Wire the circuit shown in Figure 11.

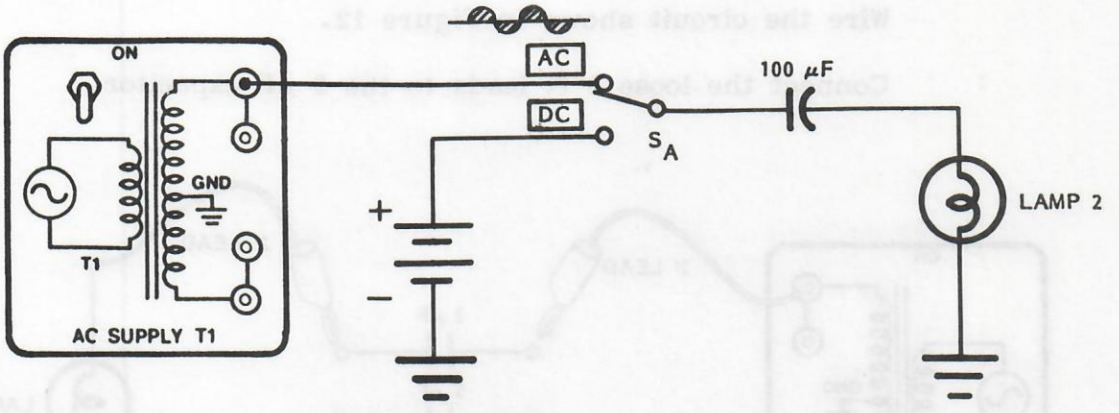


Figure 11 - Series capacitor EXPERIMENT.

With Switch SA UP, Lamp 2 is powered by ac.

With Switch SA DOWN, Lamp 2 is powered by dc.

22. Observe the lamp. Set Switch SA according to Table 1 below and record the results in Table 1.

SWITCH (UP or DOWN)	INPUT (AC or DC)	LAMP (ON or OFF)
UP		
DOWN		

TABLE 1

23. Does the capacitor "pass" ac? _____

Does the capacitor "pass" dc? _____

Does the capacitor "block" ac? _____

Does the capacitor "block" dc? _____

3.11 CAPACITOR REACTANCE

24. While a 100 μF capacitor apparently passes the full ac, lesser values of capacitance will offer some opposition as explained earlier.

Wire the circuit shown in Figure 12.

Connect the loose 2 ft leads to the 2 μF capacitor.

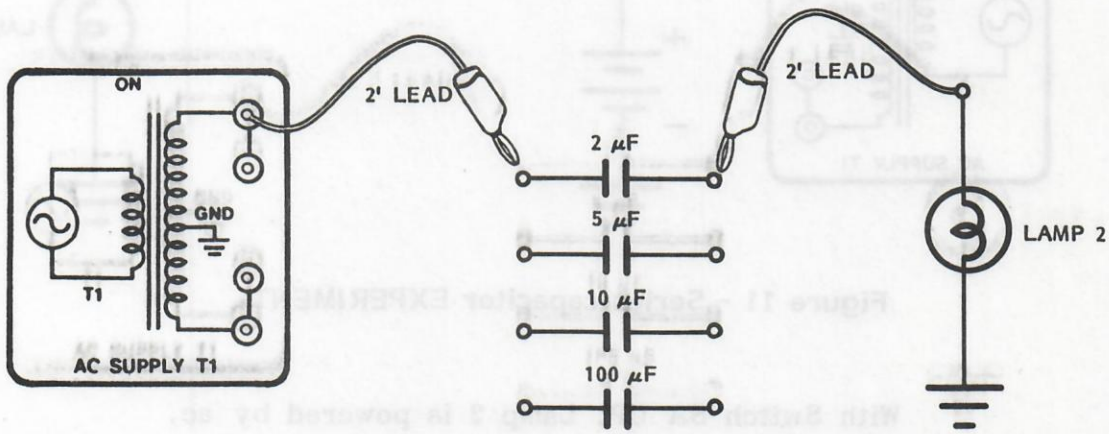


Figure 12 - Capacitive reactance EXPERIMENT.

Observe the intensity of Lamp 2 as it lights.

25. Move the two leads to the 5, 10 and 100 μF capacitors, in turn, observing the Lamp intensity.

Enter the results in the Table 2 in terms of Dim to Very Bright.

CAPACITOR	LAMP INTENSITY
2 μF	
5 μF	
10 μF	
100 μF	

TABLE 2 - Lamp intensity.

What do the results listed in Table 2 tell you about the relationship between capacitance value and capacitive reactance, X_C?

_____

_____

3.12 MEASURING CAPACITIVE REACTANCE OR AC RESISTANCE

26. Wire the circuit shown in Figure 13.

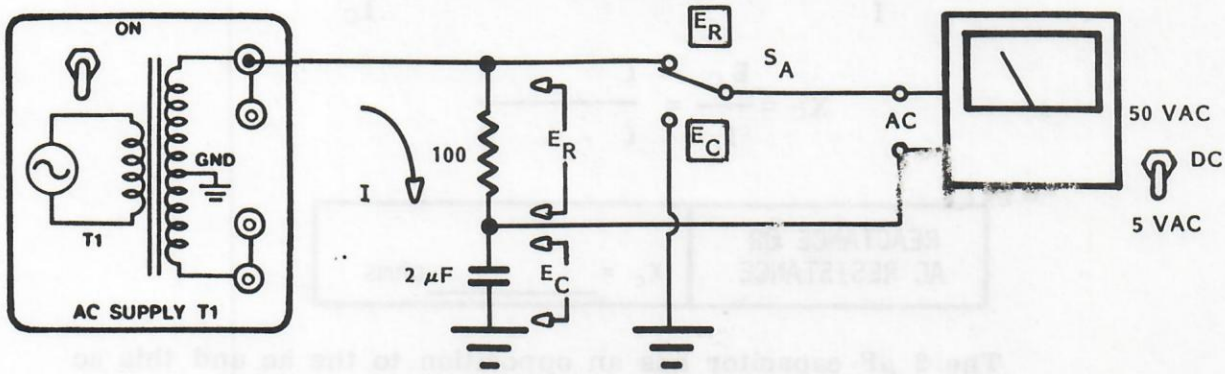


Figure 13 - Circuit to determine Xc; EXPERIMENT.

27. Place Switch SA in the UP position to measure E_R.

Set the panel meter to the 5 volt ac range and record the voltage reading below:

E_R = _____ V

28. Move the meter range switch to 50 volts ac.

Place Switch SA DOWN to read the voltage drop across the capacitor and record the voltage below.

E_C = _____ V

29. Calculate the current flow through the 100 ohm resistor which is also the current flow through the capacitor (series circuit).

$$I = \frac{E_R}{R} = \frac{(\quad)}{100}$$

I = _____ A

With I known, the capacitor opposition to ac (X_C) can now be calculated using the ac equivalent of Ohm's Law,

$$R = \frac{E}{I} \quad \text{or for the capacitor,} \quad X_C = \frac{E_C}{I_C}$$

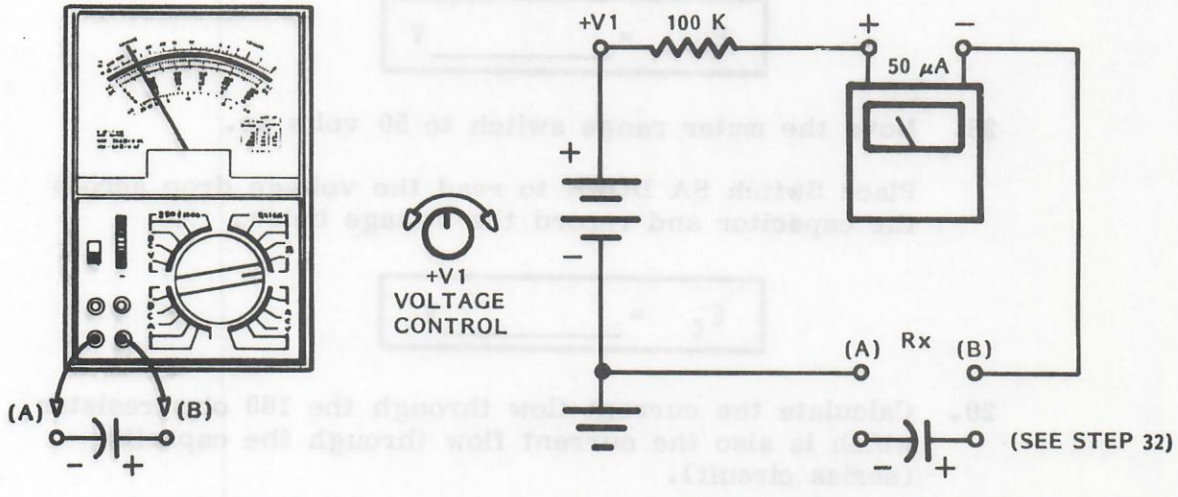
$$X_C = \frac{E_C}{I_C} = \frac{(\qquad)}{(\qquad)}$$

REACTANCE OR AC RESISTANCE	X_C = _____ ohms

The 2 μF capacitor has an opposition to the ac and this ac opposition or resistance is called CAPACITIVE REACTANCE, X_C. This is discussed further in Unit G3, Experiment No. 2.

3.13 CAPACITOR TESTING

30. An Analog ohmmeter is needed to test several capacitors on the trainer panel as shown in Figure 14(a). If none are available, wire the simple ohmmeter circuit shown in Figure 14(b) below.



(a) USING OHMMETER

(b) ALTERNATE, IF OHMMETER IS NOT AVAILABLE.

Figure 14 - Ohmmeter circuit EXPERIMENT.

While the ohmmeter of Figure 14(b) has no calibration on the meter face, you know that the extreme right equals zero ohms and the extreme left equals infinity (no current). This is enough data to evaluate capacitor charging action.

31. Short the terminals of the ohmmeter (A and B) and zero the ohmmeter (full-scale to the right). Use the zero control knob on the external meter or the +V1 Voltage Control knob for the panel meter.

32. Observe the resistance on the meter for the 100 μF capacitor applying lead A to the negative capacitor terminal and lead B to the positive terminal.

Describe the ohmmeter behavior for a period of 60 seconds.

33. Observe the resistance of the capacitors listed in Table 3 and record the ohmmeter pointer swing in terms of full, half, quarter scale, etc.

CAPACITOR	POINTER SWING
a. 10 μF	
b. 5 μF	
c. 1 μF	
d. 0.25 μF	
e. 0.01 μF	
f. 330 pF	

TABLE 3 - Capacitor deflection.

What can you conclude when comparing ohmmeter pointer deflection to capacity?

3.14 CAPACITOR RECOGNITION (OPTIONAL)

34. Your instructor will provide you with 5 different types of capacitors. In each case, identify the type (ceramic, electrolytic, mica, etc) the voltage rating and value in μF or pF. List your answers in Table 4.

CAPACITOR BOARD NO. _____

CAPACITOR	TYPE	CAPACITY	VOLTAGE
1			
2			
3			
4			
5			

TABLE 4 - Capacitor types and ratings.

CONCLUSIONS

We have learned from this experiment that:

The capacitor rating in μF or pF is an indication of how great an electron charge the capacitor can store.

Older terms for capacitance are mF for microfarad and mmF for micro-microfarad which is the same as picofarads.

The charge in coulombs is calculated from $Q = CV$.

One coulomb consists of 6.25×10^{18} electrons.

The capacitor discharge can perform work.

Capacitors block the flow of dc after the initial charging action.

Capacitors allow a flow of ac around the circuit but do not actually pass electrons across the dielectric.

Capacitors can be tested for shorts, leakage open circuits and, in some instances, for reduced capacity with an ohmmeter.

Capacitors in parallel are additive and so can store a greater charge.

Capacitors wired in series have an effective value that is less than the smallest capacitor in the series circuit and so store a reduced charge.

A capacitor will discharge when a resistance is placed across its terminals.

The energy, $\mathcal{E}$, stored in a capacitor can be calculated from $\mathcal{E} = (1/2)CV^2$.

The time it takes a capacitor to discharge through a resistance is a function of the value of C and R.

The time, in seconds, required to discharge a capacitor is determined from T = RC where R is in ohms and C is in farads.

One time constant is defined a the time required for a capacitor to drop its voltage to 37% of its full charge.

A fully charged capacitor will hold its charge for a long period of time.

The length of time a capacitor will hold its charge is a function of the insulating quality of its dielectric.

Electrolytic capacitors will dissipate their charge sooner than most other types because they have a greater amount of leakage.

Charged capacitors should not be left around; they are a shock hazard.

ASSIGNMENT

Answer the following multiple choice questions.

1. A capacitor is formed by two conductors separated by a (an):

   a. resistor.
   b. insulator.
   c. highly conductive material.
   d. ionized material.

2. The charge on a capacitor can be calculated using the formula:

   a. $Q = CV$
   b. $Q = (1/2)CV^2$
   c. $Q = C/V$
   d. none of the above.

3. A 470 μF capacitor is charged to 50 volts. The number of electrons gathered on the negative plate is closest to:

   a. 0.0235×10^{18}
   b. 6.25×10^{18}
   c. 470×10^{16}
   d. 14.69×10^{17}

4. The energy stored in a capacitor is measured in:

   a. farads.
   b. coulombs.
   c. joules.
   d. microfarads.

5. In order to discharge a capacitor:

   a. a leakage path must be provided through the dielectric.
   b. the applied voltage polarity must be maintained.
   c. an external path between the plates must be provided.
   d. none of the above.

6. A capacitor, when wired into a circuit, will:

   a. pass dc but block ac.
   b. pass both ac and dc.
   c. block both ac and dc.
   d. block dc but pass ac.

7. When testing a 250 pF capacitor with an analog ohmmeter on the X1000 scale, it is normal for the meter pointer to:

   a. swing full scale to zero and move back to infinity slowly.
   b. swing to no more than mid-scale and fall back rapidly.
   c. barely move, if at all.
   d. any of the above depending upon the capacitor voltage rating.

8. An electrolytic capacitor of 100 μF, when tested with an ohmmeter will:

   a. swing close to zero ohms and move back towards infinity slowly.
   b. normally show some leakage current.
   c. show zero ohms continually only if shorted.
   d. all of the above.

9. Two 50 μF capacitors placed in parallel provide a capacitance of:

   a. 50 μF.
   b. 25 μF.
   c. 100 μF.
   d. none of the above.

10. The energy contained in a 50 μF capacitor charged to 30 volts is closest to:

    a. 0.0225 J.
    b. 0.045 J.
    c. 0.0015 J.
    d. 0.0015 coulombs.

11. The Time Constant of an RC circuit:

    a. can be calculated from T = RC.
    b. is the time needed to discharge to 37% of the full charge.
    c. is the time needed to discharge 63% of its full voltage.
    d. all of the above.

12. A 0.5 μF capacitor discharged through a 1 megohm resistor will have a time constant of

    a. 0.5 seconds.
    b. 5×10^{-6} seconds.
    c. 0.5 volts.
    d. none of the above.

KEY TERMS

1. BLOCKING ACTION

   The action of a capacitor that prevents the flow of direct current through a circuit after the initial charging current.

2. CAPACITOR CHARGE

   The electrical energy stored in a capacitor measured in coulombs, Q, and equal to (C)(V).

3. CERAMIC

   A clay type insulating material used as a dielectric in ceramic capacitors.

4. ELECTROLYTE

   A chemical which, when conducting a current, undergoes a chemical action which causes it to deposit an oxide coating on an aluminum anode.

5. ENERGY

   The ability to perform work. Energy, $\mathcal{E}$, is stored in a charged capacitor.

6. FARAD (F)

   The unit of capacitance. A farad produces a 1 volt difference of potential when charged by 1 coulomb.

7. LEAKAGE CURRENT

   The small current that flows through an electrolytic capacitor when voltage of the proper polarity and value is applied. The larger the capacitance value the greater the leakage current.

8. MICA

   An insulator used as the dielectric in a mica capacitor.

9. PAPER CAPACITOR

   Treated paper (impregnated with wax or plastic) used as the dielectric in paper capacitors.

10. TANTALUM

    Material used for the foil, instead of aluminum, in a tantalum electrolytic capacitor.

11. TEMPERATURE COEFFICIENT

A factor used to calculate the change in capacitance due to changes in temperature. For capacitors it is expressed as parts per million per degree centigrade, ppm/°C.

12. TIME CONSTANT

The number of seconds required for a capacitor to discharge through a resistor to 36.8% of its full charge.

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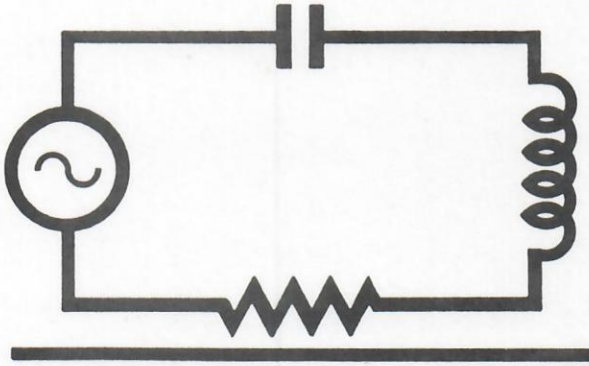

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STUDENT PROGRESS RECORD & GUIDE FOR AC PART G2

EXP./INFO.	TITLE	ASSIGNMENT		GRADE
		DATE DUE	DATE SUBMITTED	
Info. Sheet 4	Inductors			
Experiment 4	Inductor Action (CES 306)			
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Experiment 6	Diode Action			

Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part G1. Review this lesson.

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AC COMPONENTS
PART G2

Inductors

INFO SHEET 4

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Draw the symbol used for an inductor and specify its letter designation.
2. Define the unit of inductance.
3. Calculate the induced voltage in a coil.
4. Determine the energy stored in the magnetic field of a coil.
5. Calculate the inductance of a coil.
6. List the various types of inductors used in electronic circuits.
7. List the rating criteria for an inductor.
8. Calculate the total value of inductors wired in series and in parallel.
9. Define what is meant by Mutual Inductance and Coefficient of Coupling.
10. Explain the action of an inductor when dc is applied and removed.

DESCRIPTION

An INDUCTOR is generally recognized as a coil of wire. In the study of magnetism, a coil was used to produce a magnetic field and thus became an electromagnet. The inductor is a component used in ac circuits to produce an opposition to alternating or changing currents. The inductor, in this case, is not used to produce a magnetic field, although the field is created as an inherent part of the inductor operation. The inductor is defined by the letter L and is indicated in schematics by the symbol, which resembles a coil, as shown in Figure 1.

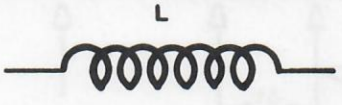


Figure 1 - Inductor symbol and its letter designation.

Consider a simple series circuit consisting of a switch, lamp, inductor and voltage source as shown in Figure 2.

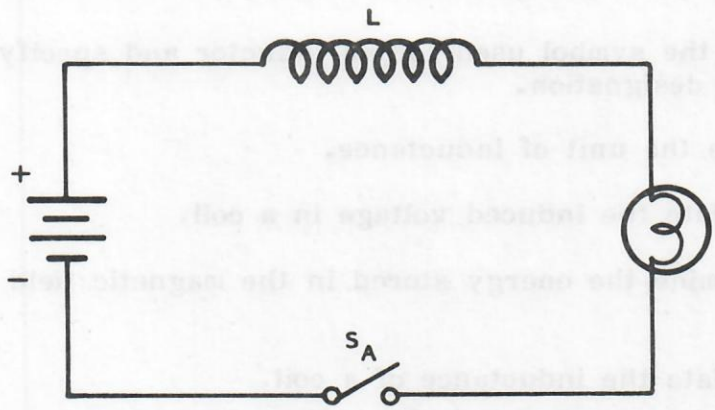


Figure 2 - Inductor in a series circuit.

When the switch in Figure 2 is closed, we would normally expect the full current to flow in the circuit, but this does not happen because of the inductor. As the current starts to flow, it creates a magnetic field in the inductor. This expanding (changing) magnetic field within the coil creates an induced voltage in the coil that opposes the applied voltage. The induced voltage can never be greater than the applied voltage and the applied voltage gradually overcomes the induced voltage. As a result, the current rises to maximum slowly. The plot of current flow against time is shown in Figure 3.

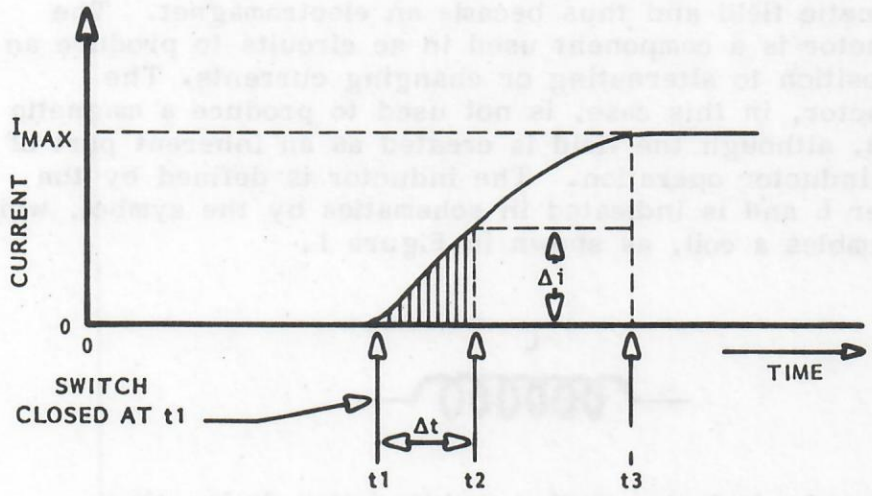


Figure 3 - Plot of current flow in a coil.

As shown in Figure 3, the current is at zero until t1 when the switch (SA in Figure 2) is closed. The current starts to rise but is opposed by the induced voltage created by the current flow (Lenz's law) and so rises slowly. At time t3 the current is at maximum and will be equal to E/R where R is the coil resistance.

If the current rise is measured from t1 to t2 which is Δt, there is a corresponding change in the current marked Δi. This can be read as a "small change in current in a small change in time."

The inductance L is a measure of how much of these magnetic effects or generation of flux or a change in magnetic flux lines, $\Delta\emptyset$, we get in a coil from a given change in current, Δi. We certainly expect that the more turns (N) a coil has, the greater the magnetic effects will be and thus the greater will be the inductance, L.

The inductance can be defined in a number of ways. Using the description from the preceding paragraph the inductance, L, is given as:

$$L = N \frac{\Delta\emptyset}{\Delta i} \qquad (1)$$

The greater the flux change ($\Delta\emptyset$) for a given current change (Δi) the greater the inductance (L).

Recalling Faraday's law covered in Information Sheet 3 of Part F1, the INDUCED VOLTAGE (e_{ind}) in the coil is larger for a faster change in flux or a greater change in flux for a given change in time ($\Delta\emptyset/\Delta t$), and greater for more turns (N).

Thus, Faraday's law is:

$$e_{ind} = N \frac{\Delta\emptyset}{\Delta t} \qquad (2)$$

Transposing equation (1) as shown below

$$L = N \frac{\Delta\emptyset}{\Delta i}$$

$$L\Delta i = N\,\Delta\emptyset$$

and substituting $L\,\Delta i$ for $N\,\Delta\phi$ in equation (2), we obtain equation (3).

$$e_{ind} = L\frac{\Delta i}{\Delta t} \qquad (3)$$

This equation refers to the Δi and Δt of Figure 3, and gives the induced voltage that results.

UNIT OF INDUCTANCE

The unit of inductance is called the HENRY (H) after the American physicist Joseph Henry (1797 - 1878). Thus in equations (1), (2) and (3) the units are

L = Henries
e_{ind} = Volts
i = Amperes
t = Seconds
N = Turns
ϕ = Webers

As noted in equation (1), we could define or measure inductance as:

$$L = N\frac{\Delta\phi}{\Delta i}$$

It is difficult, however, to measure changes in flux ($\Delta\phi$) in the air surrounding the inductor and, as noted earlier, we are not normally interested in magnetic flux in ac circuits. It is easier to measure changes in voltage, current or time and so the preferred equation is (3) which is:

$$e_{ind} = L\frac{\Delta i}{\Delta t} \qquad (3)$$

It is possible now to define and measure inductance by transposing the above equation as:

$$L = e_{ind}\frac{\Delta t}{\Delta i} \qquad (4)$$

The HENRY, the measure of inductance may now be defined as:

> A coil has an inductance (L) of 1 henry when a voltage of 1 volt is induced by a current change of 1 ampere in a time of 1 second.

For example, the current flow through a coil is increased from 0 to 2 amperes (Δi) in 4 seconds (Δt) creating a measured self-induced voltage (e_{ind}) of 6 volts. The inductance of the coil can be calculated as:

$$L = e_{ind} \frac{\Delta t}{\Delta i}$$

$$L = (6) \frac{4}{2}$$

$$\boxed{L = 12 \text{ H}}$$

A wide range of inductance values are encountered in electronics. Inductors used at power line frequencies and audio frequencies are fairly large and measured in henries. In radio frequency applications, the inductors found will measure in millihenries (mH, 10^{-3}) and microhenries (μH, 10^{-6})

As another example, consider a circuit where a current increase of 20 milliamperes occurs in 10 microseconds and the induced voltage is measured at 8 volts. The inductance is calculated as:

$$L = e_{ind} \frac{\Delta t}{\Delta i}$$

$$L = 8 \frac{10 \times 10^{-6}}{20 \times 10^{-3}}$$

$$= 8 \frac{10 \times 10^{-3}}{20}$$

$$\boxed{L = 4 \times 10^{-3} \text{ H}} \quad \text{or} \quad \boxed{L = 4 \text{ mH}}$$

In the Ed-Lab system, there are four inductors mounted on the panel as shown in Figure 4.

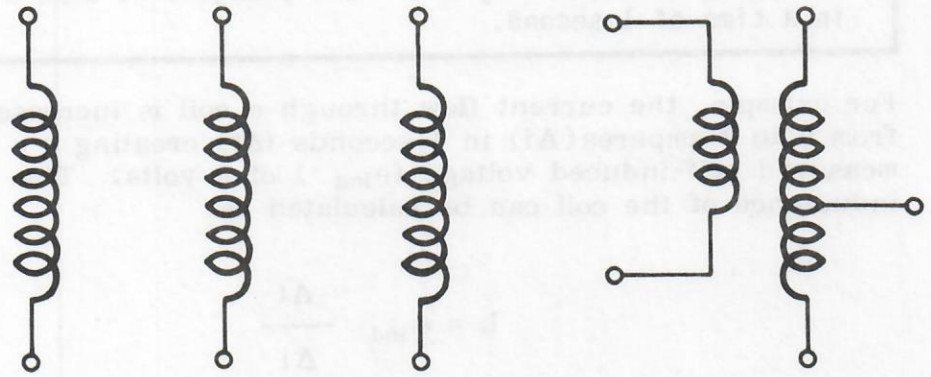


Figure 4 - Inductors available on the Ed-Lab panel.

In addition to the panel mounted inductors, there are three plug-in modules that can be used as inductors. These are:

a. CES 306, Power Transformer Module
b. CES 313, Audio Transformer Module
c. CES 318, Relay Module

CALCULATING THE INDUCED VOLTAGE

As shown before, when L, Δi and Δt are known, it is possible to calculate the expected self-induced voltage across the coil. The equation is:

$$e_{ind} = L \frac{\Delta i}{\Delta t} \qquad (3)$$

This equation indicates that the greater the value of L the greater the induced voltage (e_{ind}) will be. It further indicates that the greater the current change (Δi) in a given time (Δt), the greater the induced voltage (e_{ind}) will be.

For example, a coil has an inductance of 7 henries and the current through the coil rises from 0 to 4 amperes in 8 seconds. The induced voltage is

$$e_{ind} = L \frac{\Delta i}{\Delta t}$$

$$e_{ind} = (7) \frac{4}{8}$$

$$\boxed{e_{ind} = 3.5 \text{ volts}}$$

If the current through the same 7 H coil changed the same amount, from 0 to 4 A, in the shorter time of 0.25 seconds, the induced voltage would be:

$$e_{ind} = (7) \frac{4}{0.25}$$

$$\boxed{e_{ind} = 112 \text{ volts}}$$

This is quite a difference.

INDUCTOR ENERGY STORAGE

You learned in a previous experiment that capacitors are able to store energy in their electrostatic field and then return that energy to the circuit. Inductors can also store and return energy but the storage is in the MAGNETIC FIELD resulting from the current flow. The transfer of energy to the magnetic field represents work done by the voltage source. The greater the electrical energy (a higher current), the stronger the magnetic field.

The energy stored in an inductor is given by the equation:

ENERGY STORED IN AN INDUCTOR	$\mathcal{E} = \frac{1}{2} LI^2$

(5)

where $\mathcal{E}$ = energy stored in joules
L = inductance in henries
I = steady state current in amperes

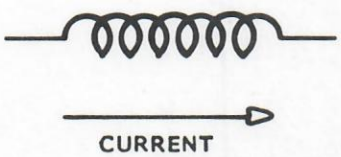
For example, if the direct current flowing through a 1.5 H inductor is 0.5 amperes, the energy stored in the magnetic field is:

$$\mathcal{E} = \frac{1}{2} LI^2$$

$$= \frac{1}{2} (1.5)(0.5^2) \text{ J}$$

$$\boxed{\mathcal{E} = 0.1875 \text{ J}}$$

By comparison, the equations for the energy stored in a capacitor, as given in Information Sheet 7, and the kinetic energy of a moving weight are shown below for comparison.



CURRENT

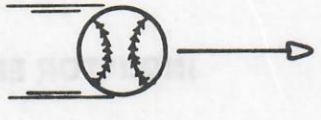
$$\mathcal{E} = \frac{1}{2} LI^2$$

$\mathcal{E}$ = energy in joules
L = inductance in H
I = Current in A

VOLTS

$$\mathcal{E} = \frac{1}{2} CV^2$$

$\mathcal{E}$ = energy in joules
C = capacitance in F
V = volts



VELOCITY

$$\mathcal{E} = \frac{1}{2} MV^2$$

$\mathcal{E}$ = energy in joules
M = mass in kg
V = velocity in meters/sec

PHYSICAL FACTORS AFFECTING INDUCTANCE

The value of inductance of a coil can be calculated by examining the physical properties of that coil. A very general formula for the calculation of inductance is given below to illustrate the related factors.

$$L = \frac{N^2 \mu R^2}{\ell} \qquad (6)$$

where L = inductance
N = number of turns
μ = core permeability
R = coil radius
ℓ = coil length

The following conclusions can be drawn from equation (6) above:

1. The greater the number of turns (N), the greater the inductance will be. Since L increases by the square of the turns, doubling N will increase L by four times. Also, reducing N by one half will result in one quarter the value of L.

2. The inductance, L, increases by the square of the coil radius. The larger the coil radius, the greater the inductance.

3. The inductance increases as the core permeability, μ, is increased.

4. The inductance decreases if the same number of turns are wound over a greater length because the magnetic field is no longer as concentrated.

CALCULATING INDUCTANCE

A commonly encountered practical formula for the calculation of inductance, similar to equation (6) but with the required multipliers to place all quantities in the same units, is:

$$L = \frac{3.2\, N^2 \mu A}{(\ell)\, 10^8} \qquad (7)$$

where L = inductance in henries
μ = permeability of the core material
A = core cross sectional area in square inches (related to R^2)
ℓ = length of the coil and core in inches

For example, to determine the inductance of a coil with the following characteristics,

N = 30 turns	A = 0.785 square inches
μ = air = 1	ℓ = 1.5 inches

use equation (7) as follows:

$$L = \frac{3.2\ N^2\ \mu A}{(\ell)\ 10^8} = \frac{3.2\ (30^2)(1)(0.785)}{1.5 \times 10^8}$$

$$L = \frac{2260.8 \times 10^{-8}}{1.5}$$

$$\boxed{L = 15\ \mu H}$$

Equation (7) is correct only for a single layer coil where the coil length is approximately ten times the coil diameter. There are many practical equations for calculating the inductance of multilayered coils that require a term defined as the FORM FACTOR, the ratio of coil diameter to length. These formulas can be found in electronic handbooks and are not within the scope of this text.

TYPES OF INDUCTORS

Inductors can be classified as:

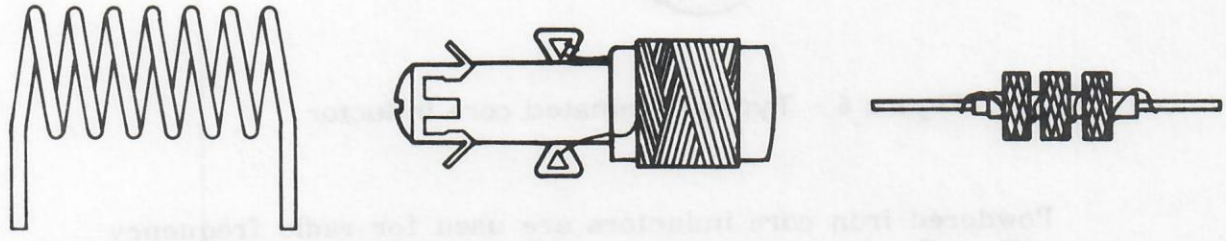
a. Fixed
b. Variable

Each is then further classified by the type of core. The core types are:

a. Air
b. Iron

Air core coils are wound on cylinders usually made of fiber, plastic, ceramic or any material that offers low losses for radio frequencies.

For very high power circuits, the air core coils are wound with heavy copper wire or hollow copper tubing and are self-supporting and use no coil form. This is shown in Figure 5(a). Air core coils wound on a wax impregnated cardboard, phenolic or ceramic forms are shown in Figures 5(b) and (c). The inductor in Figure 5(c) is a radio frequency choke wound in sections that are wired in series.



(a) SELF SUPPORTING (b) PHENOLIC FORM (c) SECTIONAL RF CHOKE

Figure 5 - Typical air core coils.

Air core coils are used in circuits that operate at radio frequencies where small values of inductance are required. For lower frequency circuits, larger values of inductance are required and so iron cores are added to the coils.

IRON CORE COILS

Adding some type of iron core to an air core coil increases the inductance greatly without requiring additional turns of wire. That this is so, is obvious when you examine equations (6) and (7) given earlier. Any increase in the permeability of the core, μ, increases L.

There are two basic types of iron cores.

a. Laminated
b. Powdered Iron

The laminated cores are used for very large inductance values and will be covered in greater detail under the subject heading of Transformers. A typical laminated core inductor is shown in Figure 6. Lamination refers to the "layers" of iron in the core.

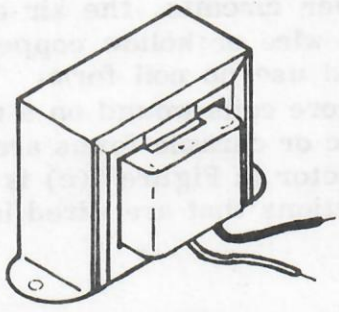
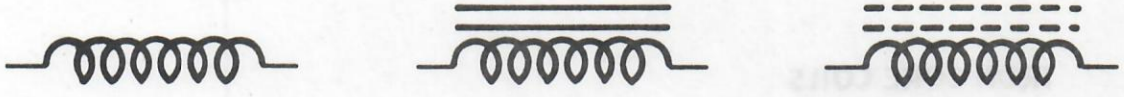


Figure 6 - Typical laminated core inductor.

Powdered iron core inductors are used for radio frequency coils. Powdered iron cores are made of fine particles of iron mixed with a bonding material and formed into the desired shape and size. Similar cores are made from ferrite materials such as nickle-ferrite or manganese-magnesium ferrite, also mixed with a bonding material.

The schematic symbols for iron and powdered iron or ferrite cores are shown in Figure 7.



(a) AIR CORE (b) IRON CORE (c) POWDERED IRON AND FERRITE CORE

Figure 7 - Air and iron core coil symbols.

VARIABLE INDUCTORS

In some instances, it is desirable to have a coil whose inductance is variable. The inductance value of a coil can be varied in several ways as shown in Figure 8. Inductor (a) has several "taps" and the total inductance between 1 and 2 or 2 and 3 is selected by switch S1. In (b) of Figure 8, a "slider" or movable contact is moved along the surface of the coil to vary the number of turns between terminals 1 and 2 or 2 and 3.

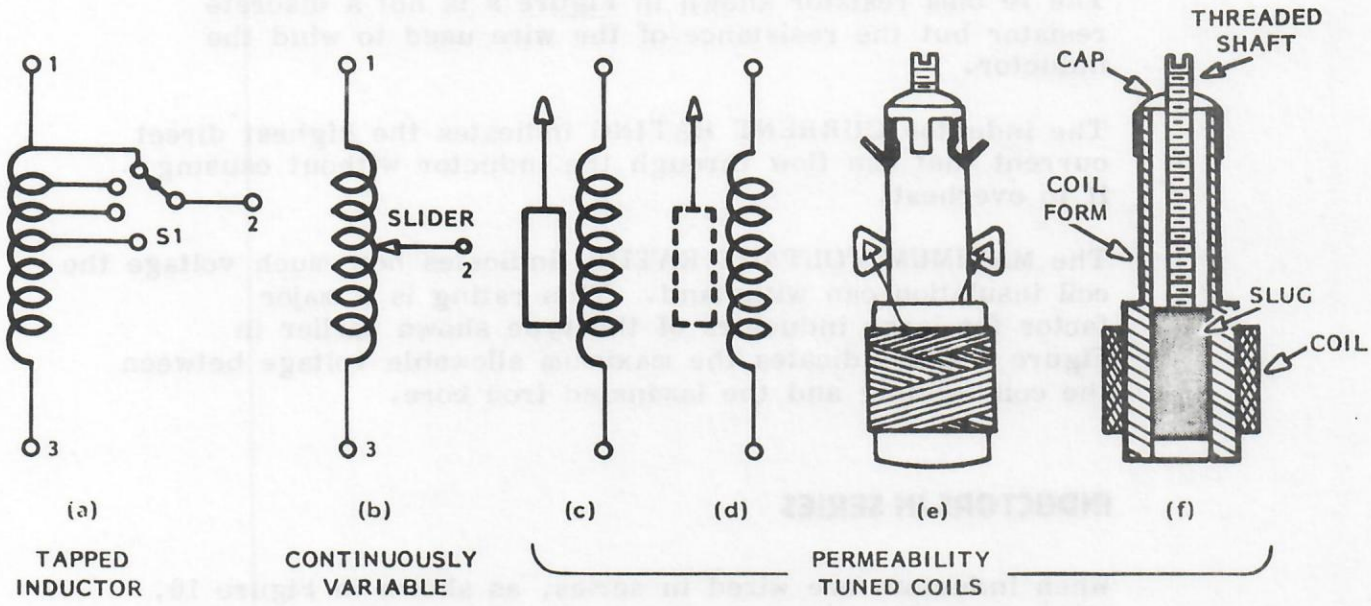


Figure 8 - Variable inductors.

The symbols for a permeability or slug tuned inductor are shown in (c) and (d) of Figure 8. A slug tuned coil (e) and its cross-section view (f) are also shown. As the slug is threaded into the coil winding area the inductance increases. The RADIO COIL, T2, mounted on the Ed-Lab trainer panel is of the type shown in Figure 8(c), (e) and (f).

INDUCTOR RATINGS

In addition to being rated by inductance in henries (H, mH or μH) inductors are also rated for the maximum voltage and current they can withstand and their dc or internal "ohmic" resistance.

The dc resistance is the total resistance of the length of the wire used to wind the core. This is the resistance that would be indicated by any ohmmeter placed across the inductor terminals. In general, the lower the resistance of the inductor, the more efficient it is. The real internal circuit of an inductor is shown in Figure 9.

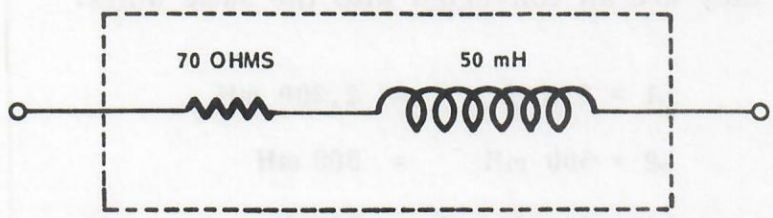


Figure 9 - Inductor showing the internal resistance.

The 70 ohm resistor shown in Figure 9 is not a discrete resistor but the resistance of the wire used to wind the inductor.

The inductor CURRENT RATING indicates the highest direct current that can flow through the inductor without causing it to overheat.

The MAXIMUM VOLTAGE RATING indicates how much voltage the coil insulation can withstand. This rating is a major factor for large inductors of the type shown earlier in Figure 6 and indicates the maximum allowable voltage between the coil winding and the laminated iron core.

INDUCTORS IN SERIES

When inductors are wired in series, as shown in Figure 10, and separated so that their magnetic fields do not interact, the equivalent inductance is the sum of the individual inductances as with resistors.

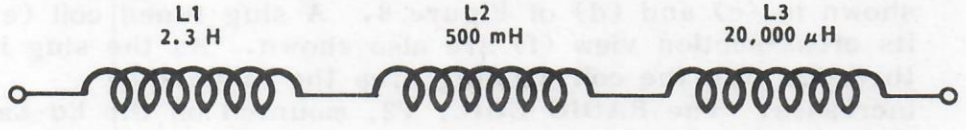


Figure 10 - Series inductances.

The total inductance for series inductors is expressed mathematically as:

$$L_T = L1 + L2 + L3 + ... L_N \quad (8)$$

where L1 ... L_N = individual inductances in henries
L_T = total inductance in henries

For example, the inductors wired in series in Figure 10 are positioned so that there is no magnetic coupling or interaction between them. Their inductances can be added after they are all converted into the same units.

L1 = 2.3 H = 2,300 mH

L2 = 500 mH = 500 mH

L3 = 20,000 μH = 20 mH

Substituting, we have:

$$L_T = L1 + L2 + L3$$

$$L_T = 2300 + 500 + 20$$

$$L_T = 2820 \text{ mH} \quad \text{or} \quad 2.82 \text{ H}$$

INDUCTORS IN PARALLEL

The total inductance of inductors in parallel is calculated in the same manner as resistors in parallel provided there is no magnetic interaction or coupling between each of the inductors.

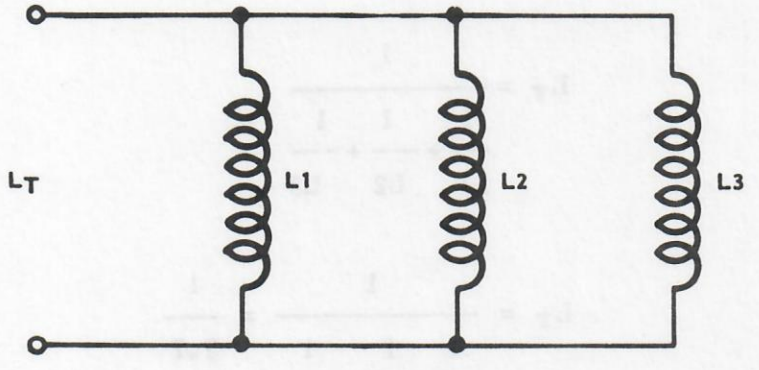


Figure 11 - Parallel inductances.

The total inductance for inductors in parallel is expressed mathematically as:

$$\frac{1}{L_T} = \frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + \cdots \frac{1}{L_N} \qquad (9)$$

or

$$L_T = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + \cdots \frac{1}{L_N}} \qquad (10)$$

When only two inductors are in parallel and they are not magnetically coupled, the total inductance can be calculated from:

$$L_T = \frac{L1 \cdot L2}{L1 + L2} \qquad (11)$$

For example, three inductors are wired in parallel. They have the following values of inductance:

$$L1 = 5\ H;\ L2 = 2\ H;\ L3 = 500\ mH$$

Change 500 mH to 0.5 H to place all the inductances in the same unit and then substitute.

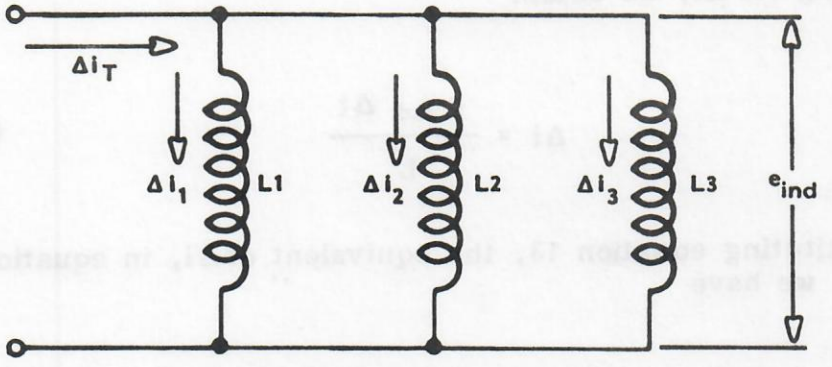
$$L_T = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3}}$$

$$L_T = \frac{1}{\frac{1}{5} + \frac{1}{2} + \frac{1}{0.5}} = \frac{1}{2.7}$$

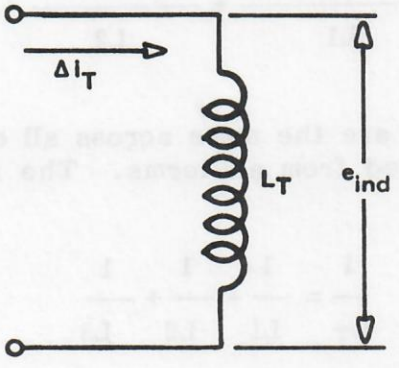
$$L_T = 0.37\ H \text{ or } 370\ mH$$

PROOF FOR PARALLEL INDUCTORS

We can prove, mathematically, that equations (9), (10) and (11) above, are valid. Consider three inductors in parallel as shown in Figure 12.



(a) THREE PARALLEL INDUCTORS, L1, L2, L3.



(b) EQUIVALENT INDUCTOR, L_T.

Figure 12 - Equivalent parallel inductors.

The single equivalent inductor in Figure 12(b) must behave the same as the three parallel inductors in Figure 12(a).

The equation for the current changes (Δi) is given by Kirchhoff's current law and is:

$$\Delta i_T = \Delta i_1 + \Delta i_2 + \Delta i_3 \qquad (12)$$

The now familiar equation (3) for the induced voltage (e_{ind}) is

$$e_{ind} = L\frac{\Delta i}{\Delta t}$$

Solving for Δi, we obtain

$$\Delta i = \frac{e_{ind}\ \Delta t}{L} \tag{13}$$

Substituting equation 13, the equivalent of Δi, in equation (12), we have

$$\Delta i_T = \Delta i_1 + \Delta i_2 + \Delta i_3 \tag{12}$$

$$\frac{e_{ind}\ \Delta t}{L_T} = \frac{e_{ind}\ \Delta t}{L1} + \frac{e_{ind}\ \Delta t}{L2} + \frac{e_{ind}\ \Delta t}{L3}$$

Since e_{ind} and Δt are the same across all of the inductors, they may be removed from all terms. The result is

$$\frac{1}{L_T} = \frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} \tag{9}$$

This is equation (9) given earlier.

MUTUAL INDUCTANCE

When two coils are separated physically, they act as two individual inductors. If, however, they are brought very close to each other, the magnetic fields interact as shown in Figure 13.

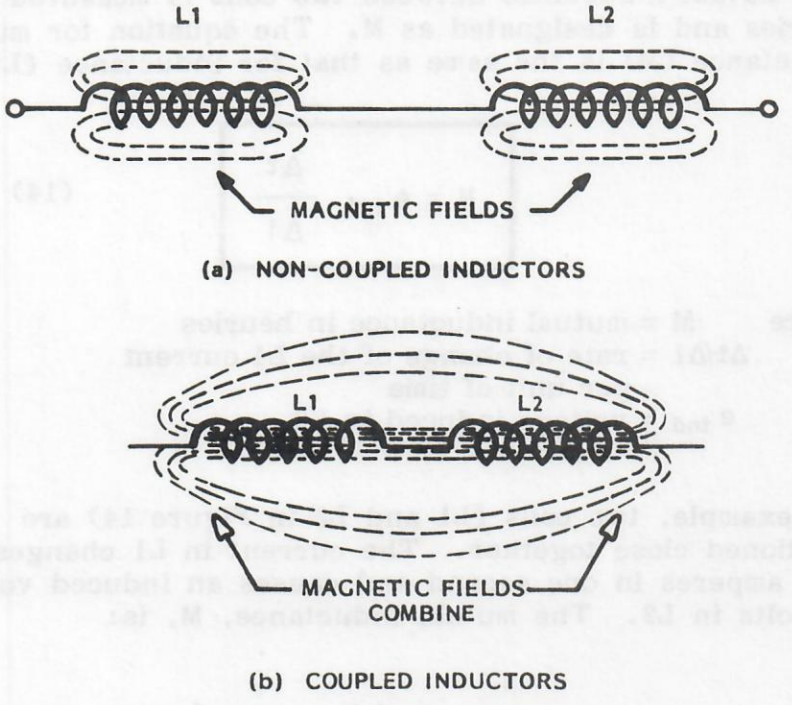


Figure 13 - Coupling between inductors.

When the magnetic flux from one coil cuts across a second coil and induces a voltage in the second coil, there exists what is called MUTUAL INDUCTANCE (M). When two coils are positioned with their axis parallel, as shown in Figures 13(b) and 14, a magnetic field developed in L1 will cut across L2 and induce a voltage in L2. The two coils are said to be COUPLED. The induced voltage (e_{ind}) will only appear in L2 if the magnetic field from L1 is changing ($\Delta\Phi$), that is, increasing or decreasing. There will be no induced voltage in L2 when the current flow through L1 is a constant value and the magnetic field is steady. Note that in Figure 14, L1 and L2 are electrically isolated from each other with no direct wire connections, but there is magnetic coupling.

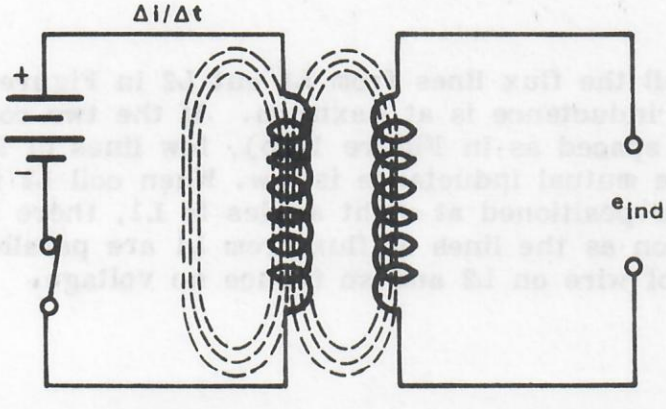


Figure 14 - Mutual inductance, M.

The mutual inductance between two coils is measured in henries and is designated as M. The equation for mutual inductance (M) is the same as that for inductance (L) and is:

$$M = e_{ind} \frac{\Delta t}{\Delta i} \qquad (14)$$

where M = mutual inductance in henries
$\Delta t/\Delta i$ = rate of change of the L1 current per unit of time
e_{ind} = voltage induced in L2

For example, two coils (L1 and L2 in Figure 14) are positioned close together. The current in L1 changes from 0 to 4 amperes in one second and causes an induced voltage of 16 volts in L2. The mutual inductance, M, is:

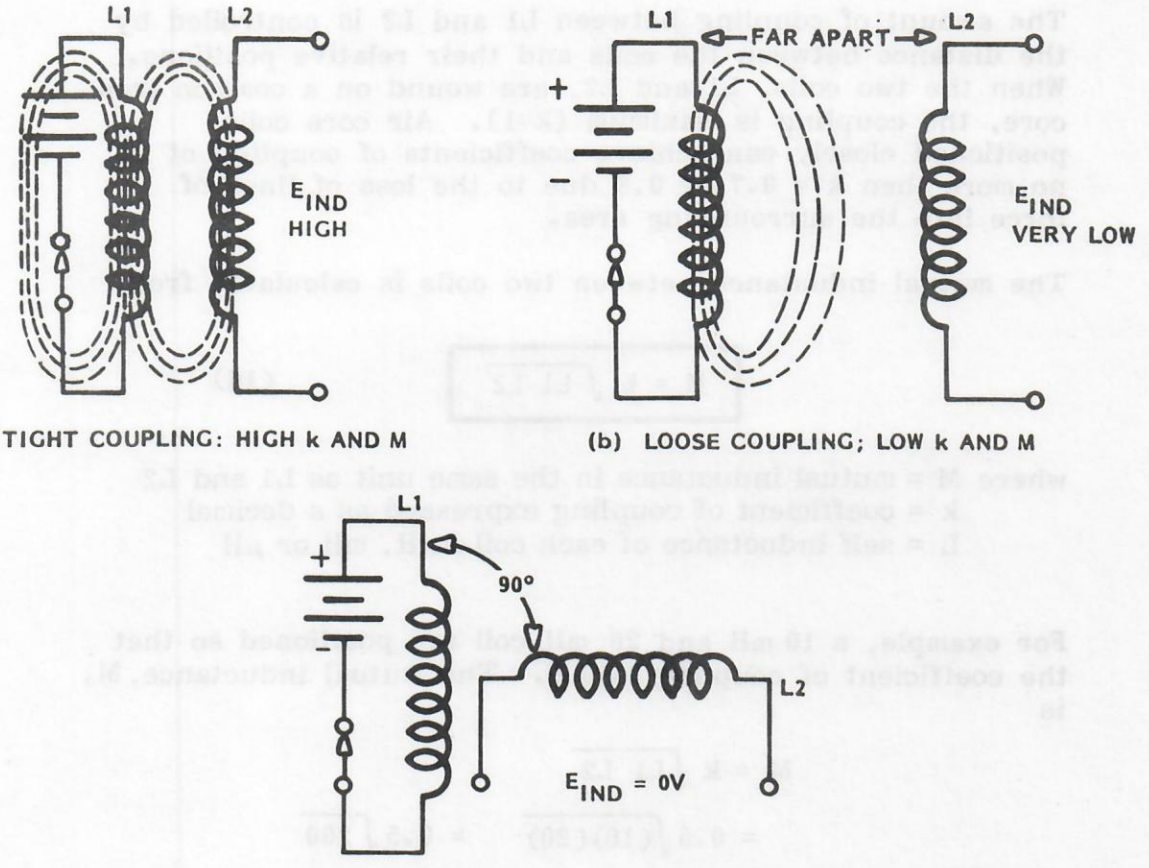
$$M = e_{ind} \frac{\Delta t}{\Delta i} = 16 \frac{1}{4}$$

$$M = \frac{16}{4}$$

$$M = 4 \text{ H}$$

COEFFICIENT OF COUPLING

When all the flux lines from L1 cut L2 in Figure 15(a), the mutual inductance is at maximum. If the two coils are widely spaced as in Figure 15(b), few lines of force cut L2 and the mutual inductance is low. When coil L2 is very far away or positioned at right angles to L1, there is no mutual induction as the lines of flux from L1 are parallel with the turns of wire on L2 and so induce no voltage.



(a) TIGHT COUPLING: HIGH k AND M

(b) LOOSE COUPLING; LOW k AND M

(c) NO MUTUAL INDUCTANCE OR COUPLING (K=0 and M=0)

Figure 15 - Effect of coil position on mutual inductance and coupling.

The COEFFICIENT OF COUPLING (k) between two coils is the ratio of the flux linking L1 and L2 to the total flux generated by L1. This is expressed mathematically as

$$k = \frac{\text{Ø linking L1 and L2}}{\text{Ø generated by L1}} \qquad (15)$$

where k = a factor between 0 and 1 with no units
Ø = lines of force

Inductors that have the maximum possible coefficient of coupling (k=1) are said to be TIGHTLY COUPLED. When the coefficient of coupling is very small, the coils are said to be LOOSELY COUPLED.

The amount of coupling between L1 and L2 is controlled by the distance between the coils and their relative positions. When the two coils, L1 and L2, are wound on a common iron core, the coupling is maximum (k=1). Air core coils positioned closely can achieve coefficients of coupling of no more than k = 0.7 or 0.8 due to the loss of lines of force into the surrounding area.

The mutual inductance between two coils is calculated from

$$M = k\sqrt{L1\ L2} \qquad (16)$$

where M = mutual inductance in the same unit as L1 and L2
k = coefficient of coupling expressed as a decimal
L = self inductance of each coil in H, mH or μH

For example, a 10 mH and 20 mH coil are positioned so that the coefficient of coupling is 0.5. The mutual inductance, M, is

$$M = k\sqrt{L1\ L2}$$

$$= 0.5\sqrt{(10)(20)} \quad = 0.5\sqrt{200}$$

$$= (0.5)\ 14.14$$

$$M = 7.07\ \text{mH}$$

The three inductors in the Ed-Lab trainer are positioned as shown in Figure 16.

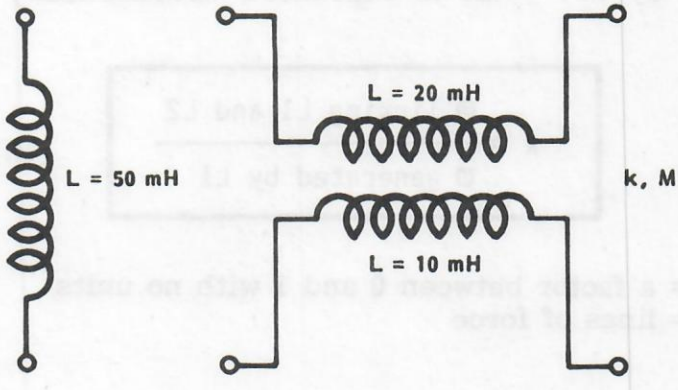


Figure 16 - Physical arrangements of the Ed-Lab inductors.

The 50 mH inductor is perpendicular to the other two inductors so there is no coupling. The 10 mH and 20 mH inductors are physically next to each other so that there is coupling (k) and a mutual inductance (M) between them.

INDUCTORS AND DC

The behavior of direct current and voltage in a purely resistive circuit has been shown earlier to be instantaneous. When the switch in Figure 17(a) is closed, the voltage appears across the resistor as in 17(b) and current flows as in 17(c).

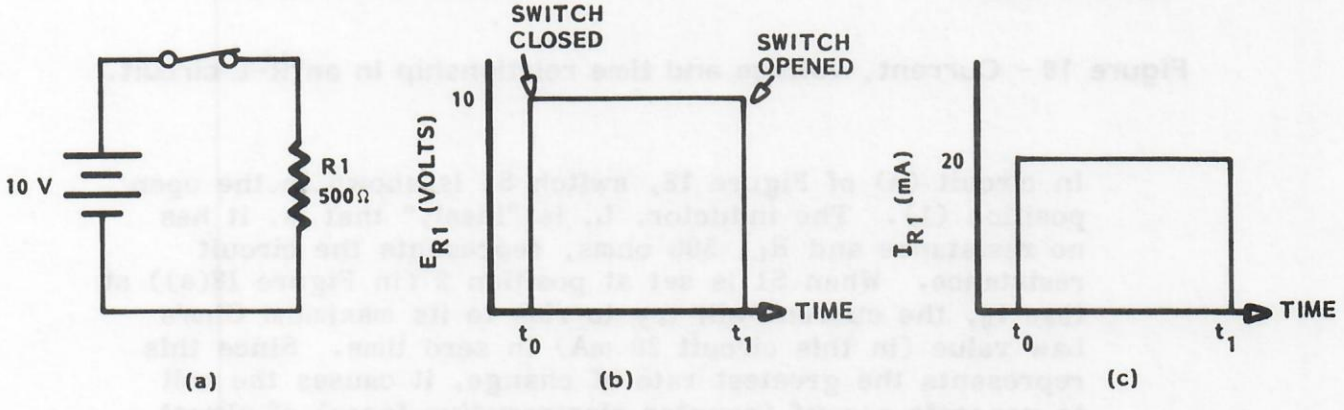
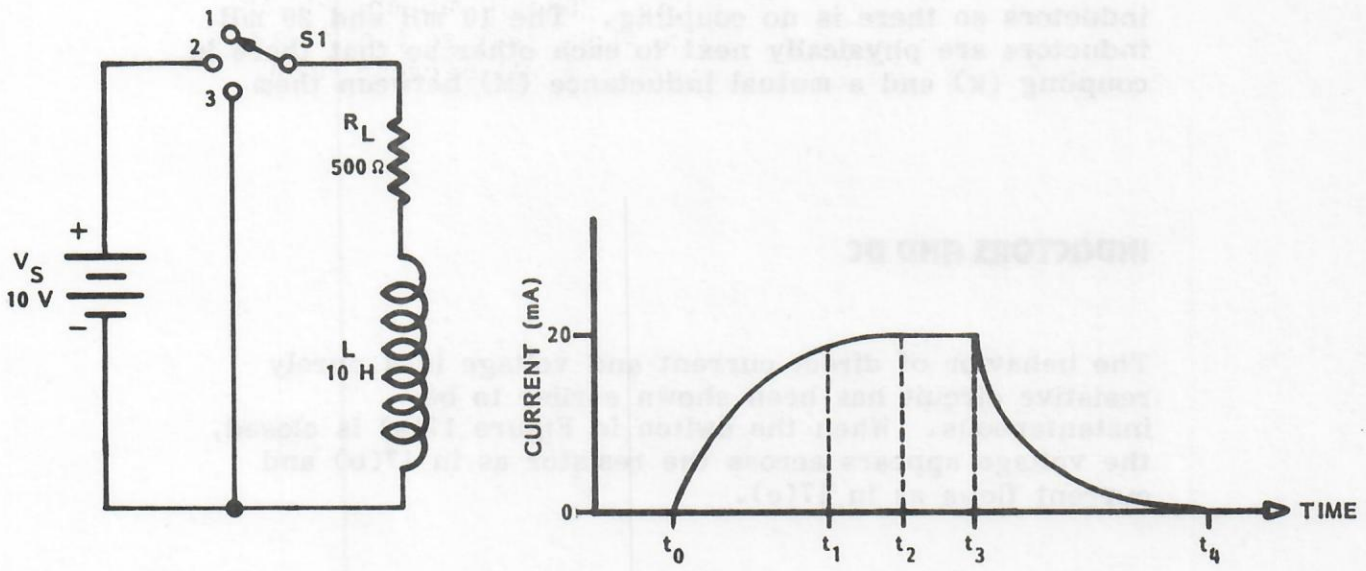


Figure 17 - Current, voltage and time relationship in a resistive circuit.

As shown, the voltage and current rise instantaneously at t_0 to their full values, remain at their full values until the switch is opened at which time E and I drop to zero instantaneously.

It has been discussed that an inductor that has a rising current develops a counter emf that opposes the current rise. Because an inductor opposes any change in current through it, the voltage and current waveforms are very different from those for the resistor shown in Figure 17 above.



(a) R-L CIRCUIT

(b) CURRENT IN R-L CIRCUIT

Figure 18 - Current, voltage and time relationship in an R-L circuit.

In circuit (a) of Figure 18, switch S1 is shown in the open position (1). The inductor, L, is "ideal," that is, it has no resistance and R_L, 500 ohms, represents the circuit resistance. When S1 is set at position 2 (in Figure 18(a)) at time t_0, the current will try to rise to its maximum Ohm's Law value (in this circuit 20 mA) in zero time. Since this represents the greatest rate of change, it causes the coil to generate a cemf (counter electromotive force) of almost 10 volts resulting in a very low initial current flow.

As the current slowly rises, the cemf gradually drops until, at t_1, the current has almost reached the full 20 mA and there is no cemf. The magnetic field is at full strength and constant. The current finally reaches its full value at t_2.

At time t_3, switch S1 is moved to position 3 which does two things. First, it removes the 10 volt source so that the current through R and L wants to stop flowing. Second, it places a direct path across R and L so that the energy contained in the magnetic field can be discharged by a current flow. Observe that at t_3, when V_S is removed from the circuit, the current through the inductor does not drop down to zero immediately. The collapsing magnetic field returns its energy to the circuit and, according to Lenz's law, attempts to maintain the current flow. The current gradually drops to zero at t_4 when all the energy in the magnetic field is gone.

INDUCTIVE KICK

Inductors are not always wired in a circuit such as shown in Figure 18(a). Another configuration is that shown in Figure 19(a) where there is no discharge path.

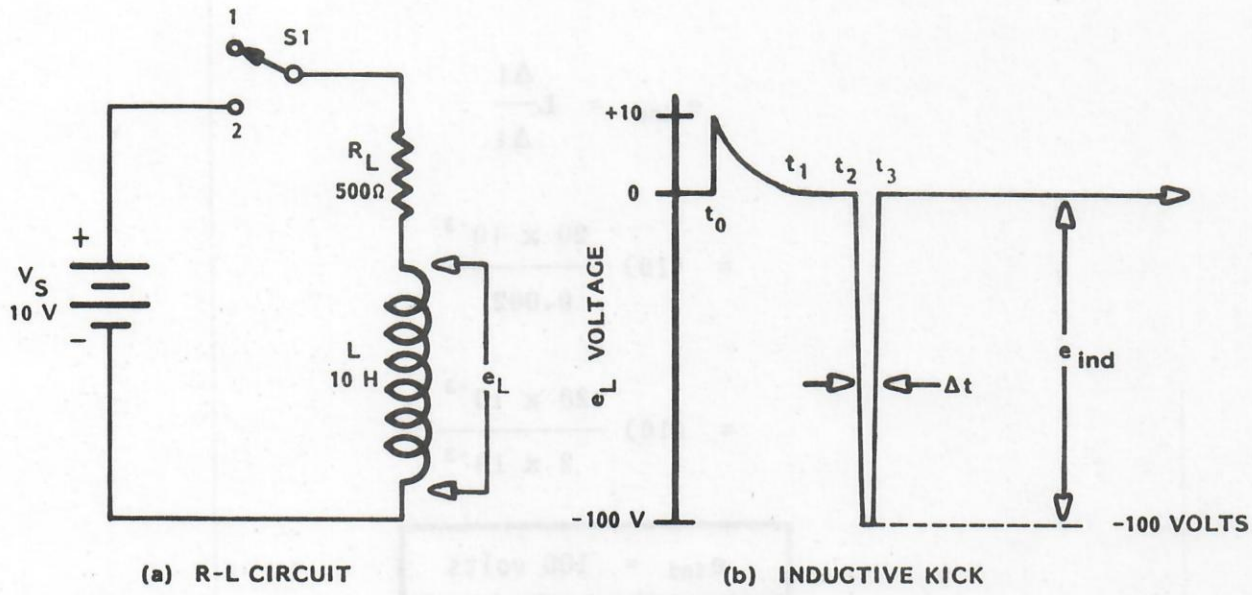


Figure 19 - Development of the inductive kick or voltage transient.

This time, we will draw the voltage waveform across the inductor. When S1 is first closed (position 2, Figure 19(a) at t_0), the full 10 volts appears across L because it is blocking current flow and there is no drop across R. As the field about L expands, I increases to 20 mA and the voltage drop across the perfect inductor (no resistance) drops to zero (at t_1) as shown in Figure 19 (b).

When S1 is opened to position 1, at time t_2 Figure 19(a), current from the voltage source stops instantly. The magnetic field about L collapses inducing a voltage that attempts to continue the current flow. The current cannot be maintained, however, because the circuit is OPEN. As a result, only a voltage is generated and it disappears when the full field has collapsed entirely. The initial induced voltage is high, usually higher than the applied voltage and its value is determined using equation (3) given earlier.

$$e_{ind} = L\frac{\Delta i}{\Delta t}$$

For example, when switch S1 is opened (position 1) at time t_2 in the circuit of Figure 19(a), for an assumed current drop of 20 mA (Δi) in 0.002 seconds (Δt), the reverse voltage or counter emf is:

$$e_{ind} = L\frac{\Delta i}{\Delta t}$$

$$= (10)\ \frac{20 \times 10^{-3}}{0.002}$$

$$= (10)\ \frac{20 \times 10^{-3}}{2 \times 10^{-3}}$$

$$\boxed{e_{ind} = 100 \text{ volts}}$$

This large voltage is called an INDUCTIVE KICK and can be dangerous to equipment and people.

INDUCTIVE KICK PROTECTIVE DIODE

The large voltage, called the Inductive Kick, can be harmful to many components in an electronic circuit and so it must be reduced. Recall the Relay Card Module used in Experiment 3, Relays, in Part F1. There was a diode placed across the relay coil to absorb any inductive kick developed by the coil. This is shown in Figure 20.

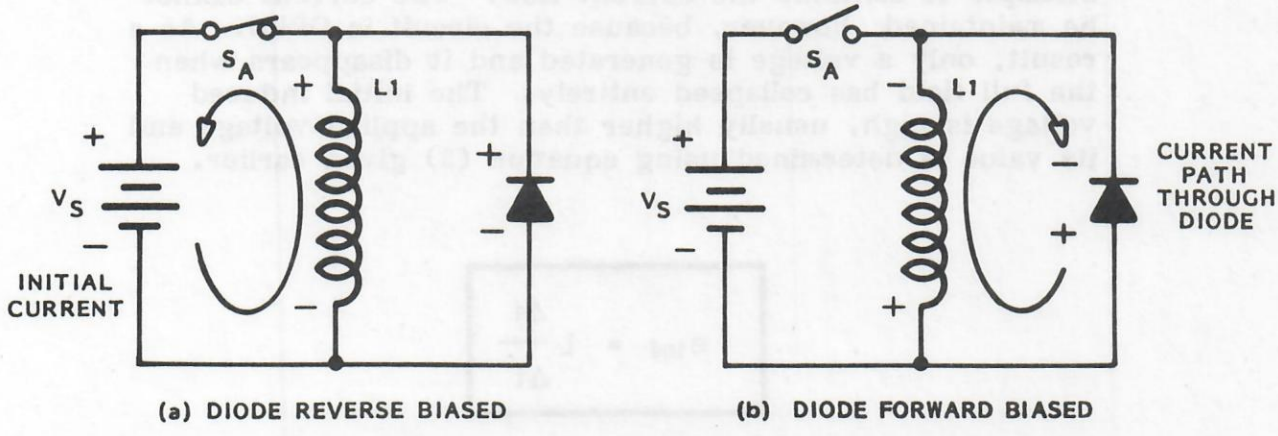


Figure 20 - Diode absorption of the inductive kick.

The diode acts as a short circuit path for current when the inductor field collapses and reverses the polarity of the voltage across the coil. The diode conducts and discharges the energy that was stored in the magnetic field thus preventing the inductive kick from developing.

The operation of the diode was introduced briefly in Information Sheet 1, Concepts of AC, and is covered in greater detail in a later information sheet and experiments on semiconductors.

In Figure 20 (a), when the switch is closed, Vs is applied to the inductor and its parallel diode. The diode, however, is reversed biased and no current flows through it. When the switch is opened in (b), the field around L1 collapses and the self induced voltage across the coil reverses polarity as shown. This polarity is correct to forward bias the diode so that it conducts and discharges the energy stored in the magnetic field.

CONCLUSIONS

We have learned from this information sheet that:

Inductance is the property to create an induced voltage that opposes any change in the current flow through the inductor.

The letter designation for the inductor is L.

The symbol for the inductor is .

The inductor is also called a coil or a reactor.

Faraday's law, stated in equation form is:

$$e_{ind} = N \frac{\Delta \phi}{\Delta t}$$

Lenz's law states that the direction of induced current in a coil opposes the magnet field change that created it.

The voltage induced in a coil by the magnet field created by the coil's own current is called the "self-induced" voltage.

The unit of inductance is the HENRY, H.

A coil has 1 H of inductance when a 1 A change of current in 1 second causes a self induced voltage of 1 V.

The inductance of a coil can be expressed mathematically as:

$$L = e_{ind} \frac{\Delta t}{\Delta i}$$

The induced voltage of a coil can be calculated from:

$$e_{ind} = L \frac{\Delta i}{\Delta t}$$

An inductor stores energy in its magnetic field and returns it to the circuit when the current through the inductor is reduced.

The energy, in joules, stored in a magnetic field, is given by

$$\mathcal{E} = \frac{1}{2} L I^2$$

The value of an inductor is based on the radius of the winding, the number of turns, the winding length and the core permeability.

The general formula for inductance is

$$L = \frac{N^2 \mu R^2}{\ell}$$

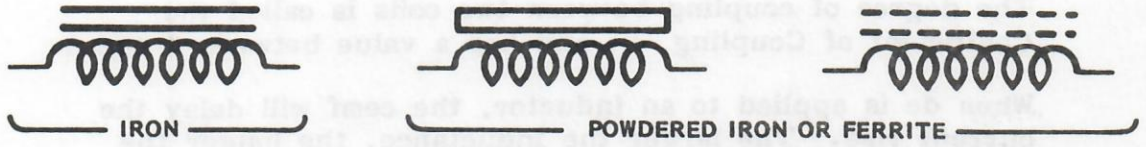
The above formula is valid for a single layer air core coil with a length 10 times its diameter.

Inductors can be classified as fixed or variable, and by types of cores.

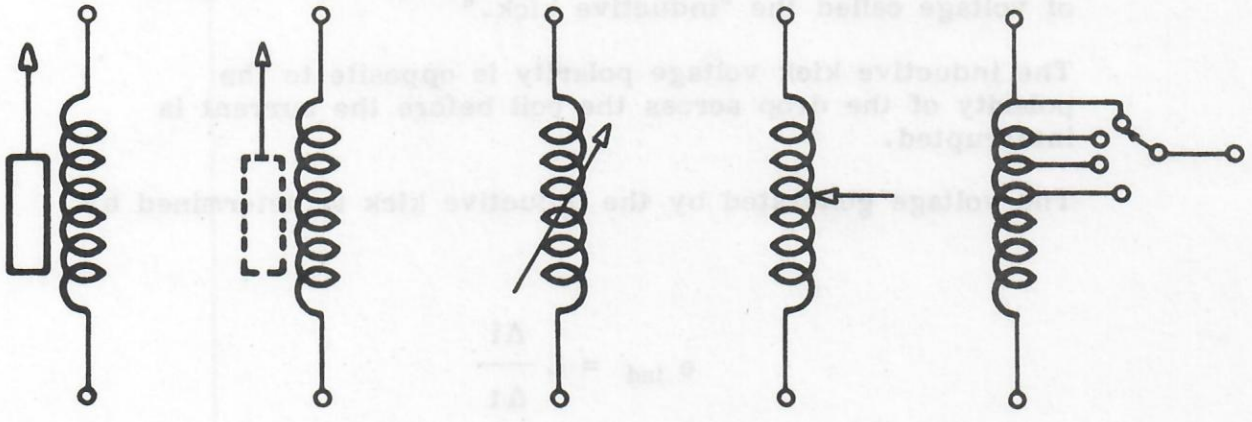
Large inductors use laminated iron cores and are used in low frequency circuits.

Coils that are used for high frequencies (radio frequencies) are air core or have powdered iron or ferrite cores.

The symbols for inductors with cores are:



Variable inductor symbols are:



Coils are rated by inductance in H, mH or μH.

Inductors are also rated by their dc resistance, maximum allowable direct current and breakdown voltage.

Inductors in series are additive, $L_T = L1 + L2 \text{ --- } + L_N$.

Inductors in parallel are like resistors in parallel, the total inductance is less than the lowest inductor in the network.

Inductors in parallel are equal to

$$L_T = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3}} \quad \text{and} \quad L_T = \frac{L1 \cdot L2}{L1 + L2}$$

Two coils placed in parallel or on the same axis can be coupled by the magnetic field generated by one of the coils.

The magnetic coupling of the two coils is called Mutual Inductance, is shown as M and is measured in henries.

Coils placed at right angles have no mutual inductance.

The degree of coupling between two coils is called the Coefficient of Coupling, k, and has a value between 0 and 1.

When dc is applied to an inductor, the cemf will delay the current rise. The larger the inductance, the longer the delay.

When the dc current flow through an inductor is broken, the rapid shrinking of the field into the coil generates a pulse of voltage called the "inductive kick."

The inductive kick voltage polarity is opposite to the polarity of the drop across the coil before the current is interrupted.

The voltage generated by the inductive kick is determined by

$$e_{ind} = L\frac{\Delta i}{\Delta t}$$

The inductive kick can be prevented in circuits, where it may be harmful, by the use of a properly connected diode across the coil.

ASSIGNMENT

Answer the following True-False questions.

1. Inductance is the ability of a component to oppose any change in voltage across it. _____

2. The inductor letter designation is L. _____

3. Faraday's law is expressed mathematically as:

$$e_{ind} = N \frac{\Delta \phi}{\Delta t}$$

_____

4. Lenz's law states that the direction of the induced current will be such that its own magnetic field will oppose the magnetic action that created it. _____

5. The pulse of voltage that appears across an inductor when the current is cut off is called a "transient." _____

6. An inductance of 1 H exists when a counter emf of 1 volt is induced by a 2 ampere current change in one half second. _____

7. A 2000 mH coil is equal to 20 H. _____

8. Given that $\Delta i/\Delta t$ is equal to 20 and the inductance is 50 mH, the induced voltage will be approximately 25 volts. _____

9. If delta t in an inductor is reduced the induced voltage will decrease. _____

10. Energy can be stored in the magnetic field of the inductor to be returned to the circuit when the current through the inductor is decreased. _____

11. Given a current of 0.25 A and an inductance of 50 mH, the stored energy is 0.0015 H. _____

12. Doubling the number of turns on a coil increases the inductance four fold. _____

13. Increasing the length of a coil winding but maintaining the same number of turns does not affect the inductance value. _____

14. Inductance values may be varied by placing taps on a winding or moving the position of a core. ____

15. In a slug tuned coil, maximum inductance coincides with maximum slug insertion into the coil winding area. ____

16. Inductors designed for use at radio frequencies (high frequencies) have cores made of laminated iron. ____

17. Inductors are rated for inductance, resistance and breakdown voltage. ____

18. The higher the breakdown voltage rating the more efficient a coil is. ____

19. Two inductors wired in series will produce a higher inductance that equals the sum of both inductors. ____

20. Inductors in parallel behave like capacitors in parallel. ____

21. Two inductors placed at right angles to each other have minimum mutual coupling. ____

22. Two inductors placed at right angles to each other have a coefficient of coupling approximately equal to 1. ____

23. Two inductors positioned so that they have a coefficient of coupling of 1 are said to be loosely coupled. ____

24. The rise of direct current in an inductor is delayed. The larger the inductor the greater the delay. ____

25. The faster a magnetic field around a coil collapses, the greater the induced voltage. ____

Perform the following.

26. Draw the symbols for the components listed.

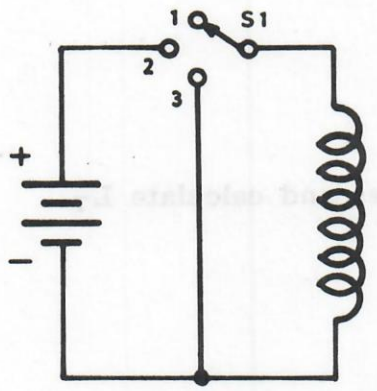
a. Air Core Coil

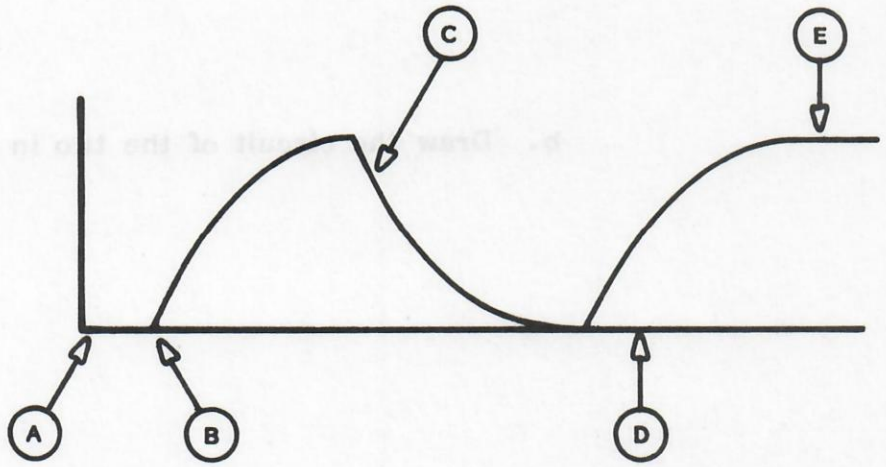
b. Laminated Iron Core Coil

c. Powdered Iron Variable Core Coil

d. Tapped Inductor and Switch

27. Indicate the position of switch S1 for each point on the graph.





A. _____ C. _____ E. _____

B. _____ D. _____

28. a. Calculate the inductance of an air core coil given the following:

number of turns = 60
coil radius = 1 inch
coil length = 10 inches

b. Calculate the new inductance given that a core with a μ of 5 is added.

29. Two inductors are available, one 10,000 μH and one 50 mH.

a. Draw the circuit of the two in parallel and calculate L_T.

b. Draw the circuit of the two in series and calculate L_T.

30. Draw the circuit of a dc power source, a switch, an inductor and a diode connected to the inductor to absorb the inductive kick.

KEY TERMS

1. BREAKDOWN VOLTAGE

   The voltage at which the insulation between the inductor winding and the core breaks down.

2. COEFFICIENT OF COUPLING

   The degree of magnetic coupling between two inductors.

3. DELTA (Δ)

   The Greek letter, delta, means change. Thus Δt means a change in t which represents time.

4. ENERGY

   The ability to perform work. Energy, $\mathcal{E}$, is stored in the magnetic field of an inductor and is measured in joules, J.

5. FERRITE

   A powdered magnetic material such as nickle ferrite combined with a binding material and compressed into the desired form and size.

6. HENRY

   The unit of inductance named after Joseph Henry (1797 - 1878), an American physicist. It is written as henry and abbreviated as H.

7. INDUCED VOLTAGE

   The voltage created across an inductor by an external magnetic field or the coil's own magnetic field generated by the current flowing through it.

8. INDUCTANCE

   That property of a component that opposes any change in the current flowing through it.

9. INDUCTIVE KICK

   The pulse of voltage that appears across an inductor when the current flow is broken suddenly. The voltage generated can be very much greater than the source voltage.

10. L

The symbol used to indicate a coil or inductor.

11. LAMINATED CORE

An iron core for a coil formed from layers of metal rather than a solid piece of metal.

12. LOOSE COUPLING

Two coils positioned so that the mutual inductance is relatively low.

13. MICROHENRY

One millionth of a henry or H x 10^{-6} and abbreviated as μH.

14. MILLIHENRY

One thousandth of a henry or H x 10^{-3} and abbreviated as mH.

15. MUTUAL INDUCTANCE

A measure of the voltage induced in a coil B by a changing flux from coil A. The factors that determine mutual inductance, L_M, are the coefficient of coupling and inductances L1 and L2. Thus:

$$L_M = k \sqrt{L1\ L2}$$

16. POWDERED IRON

Iron particles suspended in a binding material and pressed into the desired shape for use as efficient cores in high frequency coils.

17. RADIUS

A line drawn from the center of the circle to the circumference. It is equal to half the diameter.

18. SLUG TUNED

Varying the inductance of an inductor by inserting a slug of powdered ferrite or iron into the magnetic field area of the inductor to increase L.

19. TIGHT COUPLING

Two coils positioned so that the mutual inductance is very high.

20. TRANSIENT

A momentary pulse of voltage or current. A sudden change in level that exists for a very short period of time.

21. VARIABLE INDUCTOR

A coil whose inductance can be varied by taps, slider or permeability changes.

Inductor Action 4

OBJECTIVES

When you finish this experiment, you will be able to:

1. Demonstrate the opposition an inductor develops to a starting current.
2. Demonstrate and explain how an inductor develops an "Inductive Kick."
3. Show how an inductor will conduct dc but oppose ac.
4. Draw the symbol for an LED and briefly describe its operation.
5. Calculate the opposition of an inductor to the flow of 60 Hz ac.

ADDITIONAL EQUIPMENT

a. Power Transformer Module CES 306

DESCRIPTION

Your first experiments in dc circuits used the simple series circuit shown in Figure 1.

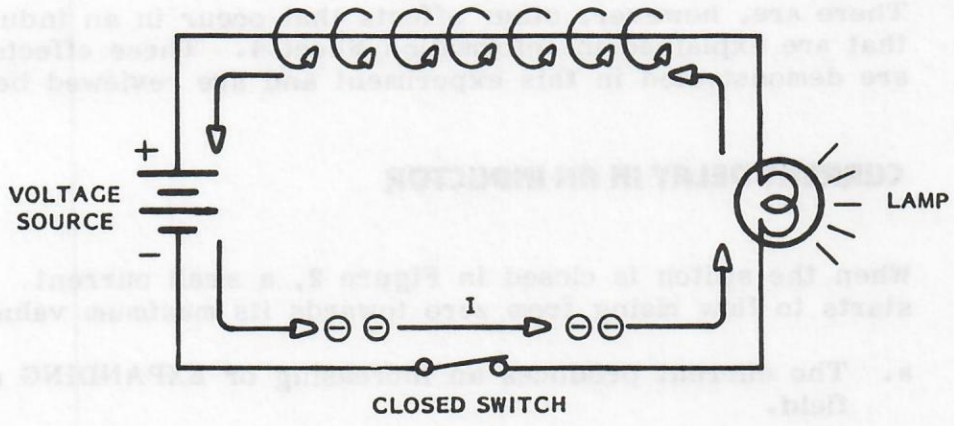


Figure 1 - Simple series circuit.

When the switch in Figure 1 is closed, current (I) flows and the lamp glows. At the same time, as was studied in magnetism, invisible lines of magnetic flux develop along the full length of the connecting wires. These lines of flux are so weak that they are ignored.

If the connecting wire is lengthened and formed into a coil as shown in Figure 2, several important things happen.

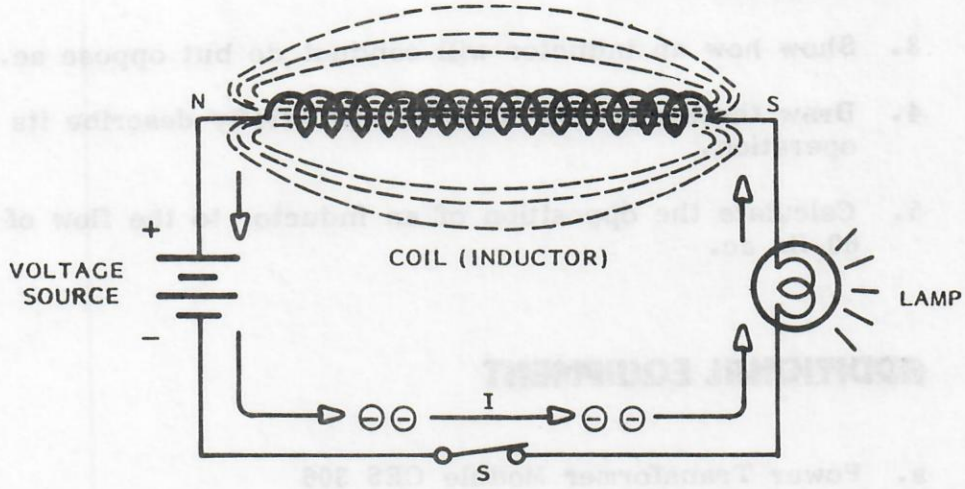


Figure 2 - Coil (inductor) in a series circuit.

The magnetic fields formed by each turn of wire add and concentrate in the center of the coil as described and demonstrated earlier. When an iron core is placed in the center of the coil, a much stronger magnetic field is produced for the same current flow.

There are, however, other effects that occur in an inductor that are explained in Information Sheet 4. These effects are demonstrated in this experiment and are reviewed below.

CURRENT DELAY IN AN INDUCTOR

When the switch is closed in Figure 2, a small current starts to flow rising from zero towards its maximum value.

a. The current produces an increasing or EXPANDING magnetic field.

b. The expanding magnet field induces a counter emf in the coil which, in accordance with Lenz's law, opposes the applied voltage that produced the field. This opposing action slows the rise of current.

c. The result of the induced voltage is that the current cannot start to flow quickly in an inductive circuit. When the switch in Figure 2 is closed, the lamp will not glow immediately but rise slowly to full brilliance. The greater the inductance of the coil, the longer it will take the lamp to reach full intensity. This effect cannot be demonstrated in this experiment because the delay developed by the inductors used is too small to be observed.

INDUCTIVE KICK

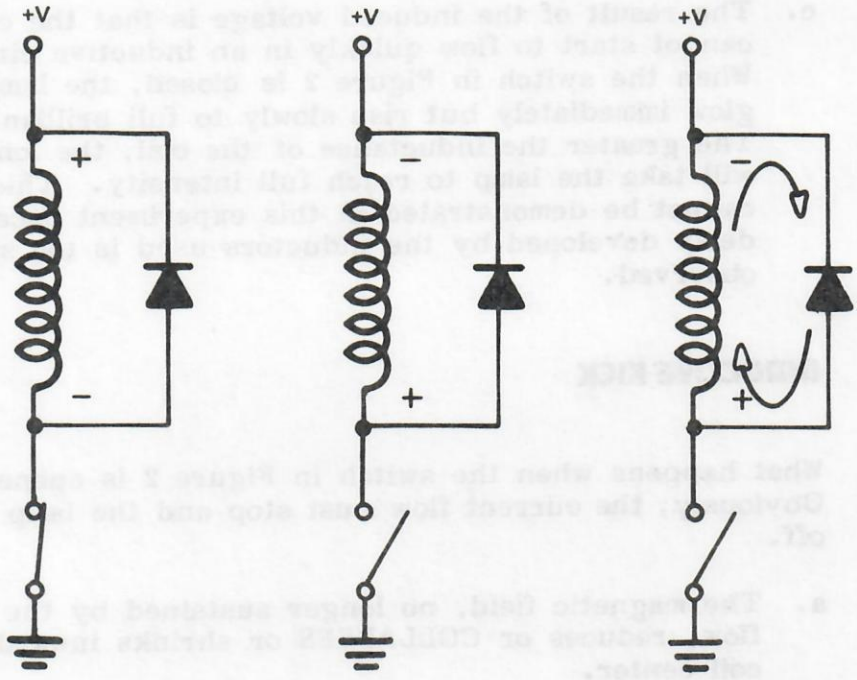
What happens when the switch in Figure 2 is opened? Obviously, the current flow must stop and the lamp will turn off.

a. The magnetic field, no longer sustained by the current flow, reduces or COLLAPSES or shrinks inward toward the coil center.

b. This changing magnetic field, going from maximum strength to zero strength, induces a voltage across the coil opposite to the polarity of the voltage source that generated the magnetic field. This voltage pulse generated by the shrinking field attempts to maintain the current flow but it cannot because the circuit is open and this momentary (transient) voltage pulse disappears when the field disappears.

c. The amount of the induced voltage depends upon the speed of the current change. When the switch is snapped open, the change is fast and therefore the voltage can be very high, even hundreds of volts when the original voltage was only 9 volts.

Often the "inductive kick" or self-induced voltage is so high that it can damage other electronic components in the circuit. To suppress the inductive kick in practical electronic circuits, a diode is wired across the coil as shown in Figure 3. In Figure 3(a), current flows in the coil but the polarity of the voltage drop across the coil reverse biases the diode and the diode does not conduct.



(a) DIODE REVERSE BIASED (b) SWITCH OPEN (c) DIODE FORWARD BIASED

Figure 3 - Diode used to dissipate the magnetic field energy.

When the switch is opened as in Figure 3(b), the field collapses and generates a momentary voltage (transient or pulse) of the opposite polarity which forward biases the diode. The diode conducts, Figure 3(c), placing a short-circuit path for current across the coil, draining the energy from the magnetic field. The conducting diode keeps the voltage or inductive kick very low, under 1 volt. Without the diode it could be as high as 100 volts or more.

Using a mechanical switch such as on the Ed-Lab 651 panel, the pulse appeared on an oscilloscope as 0.2 mS wide with an inductive kick of 192 volts with a coil voltage of only 1 volt.

OPPOSITION TO AC

When dc is first applied to an inductor, the starting current flow creates a self-induced voltage that opposes the initial current flow. In effect, the self-induced voltage acts as a temporary resistance and initially opposes the current flow. After a brief period, the induced emf disappears and the current reaches its normal level determined by E and R.

When ac is applied, the induced emf also opposes the current flow but the oppositon is continuous because the current is constantly changing amplitude and direction. When the induced emf disappears, the applied voltage reverses polarity and another reversed induced emf appears and so on. The coil REACTS to ac much more than it does to dc and so the coil's opposition to the flow of ac is much greater. This opposition by a coil to ac is called REACTANCE and identified by the letter X as the resistance in dc is identified by the letter R. Reactance, X, is also given in ohms. Since the reactance is caused by an inductance it is further identified as INDUCTIVE REACTANCE and labeled X_L. As an example, an inductor can have a dc resistance of 10 ohms and an ac inductive reactance, X_L, of 8,000 ohms. The subject of X_L is covered in detail in a later experiment.

The inductor then, "passes" dc but opposes or "blocks" ac. This is just the opposite of the capacitor which "blocks" dc and "passes" ac.

CES 306 TRANSFORMER MODULE

A transformer consists of two or more coils wound on a common core as shown in Figure 4(a) and the appearance of a typical unit is shown in 4(b).

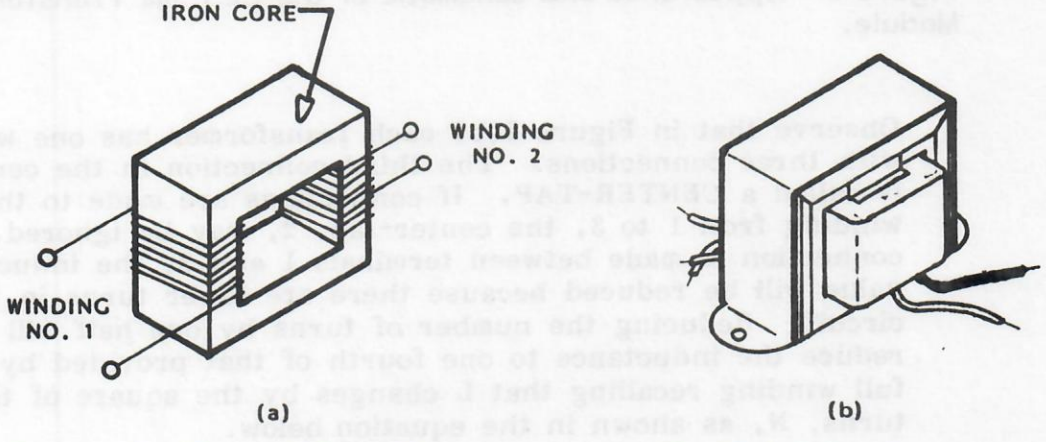


Figure 4 - Typical Transformer construction and appearance.

Transformer construction and operation are discussed in detail in the next information sheet and experiment. For now, all that is needed is to understand that when only one winding on the transformer is used, that winding acts as an inductor.

The transformer used as an inductor in this experiment is one of two transformers mounted on the CES 306 plug-in transformer card module shown in Figure 5 along with the pin connections.

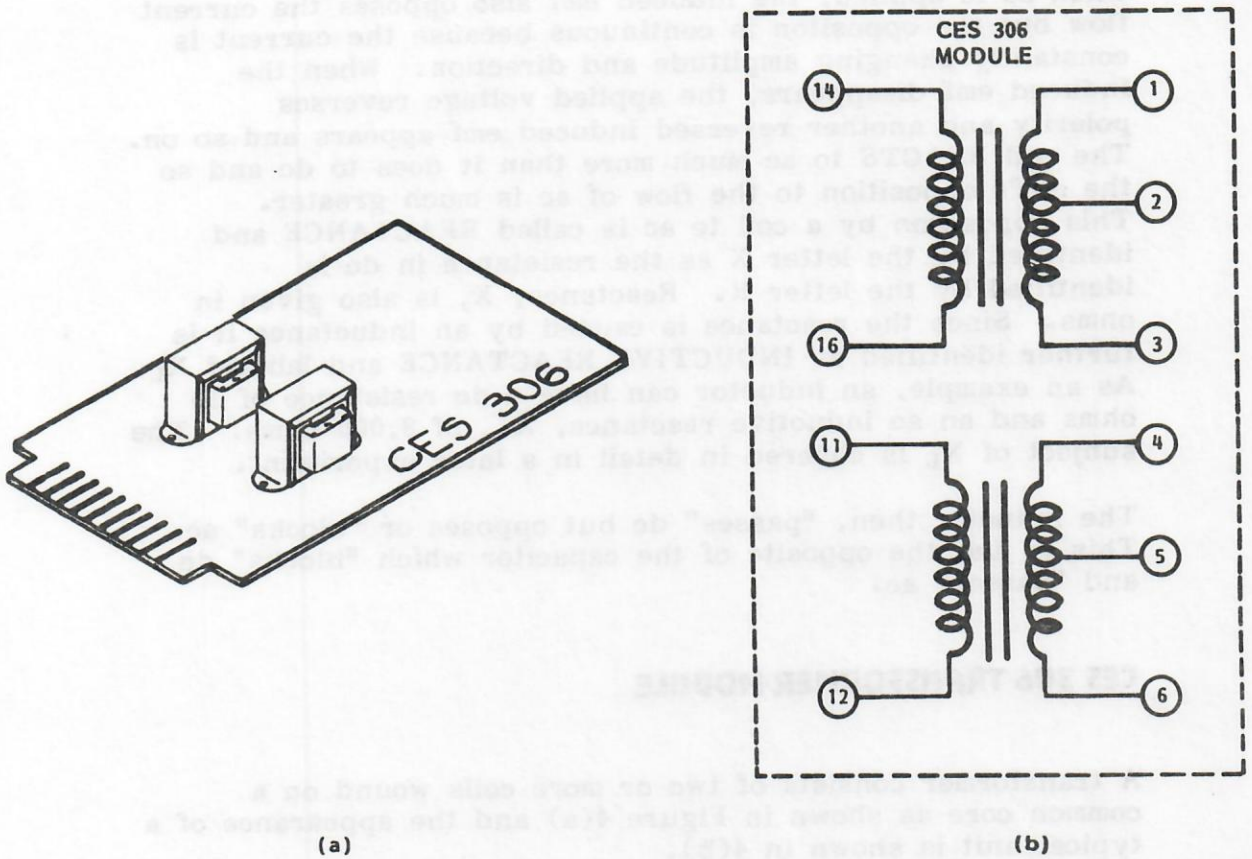


Figure 5 - Appearance and schematic of the CES 306 Transformer Module.

Observe that in Figure 5(b) each transformer has one winding with three connections. The third connection in the center is called a CENTER-TAP. If connections are made to the winding from 1 to 3, the center-tap, 2, may be ignored. If connection is made between terminals 1 and 2, the inductance value will be reduced because there are fewer turns in the circuit. Reducing the number of turns by one half will reduce the inductance to one fourth of that provided by the full winding recalling that L changes by the square of the turns, N, as shown in the equation below.

$$L = \frac{N^2 \mu R^2}{\ell}$$

where L = Inductance
N = number of turns
μ = permeability of core
R = core radius
ℓ = coil length

LED LAMP

Also used in this experiment is the Light Emitting Diode referred to as an LED lamp or simply an LED. The LED is a special type of diode that emits light when current flows through it in the normal or forward direction. The symbol for the LED is shown in Figure 6(a) and (b) shows how it must be connected into a circuit to light.

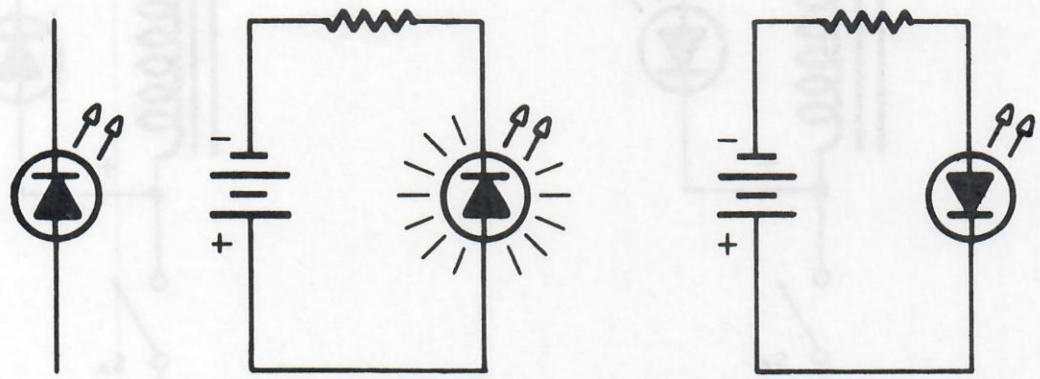
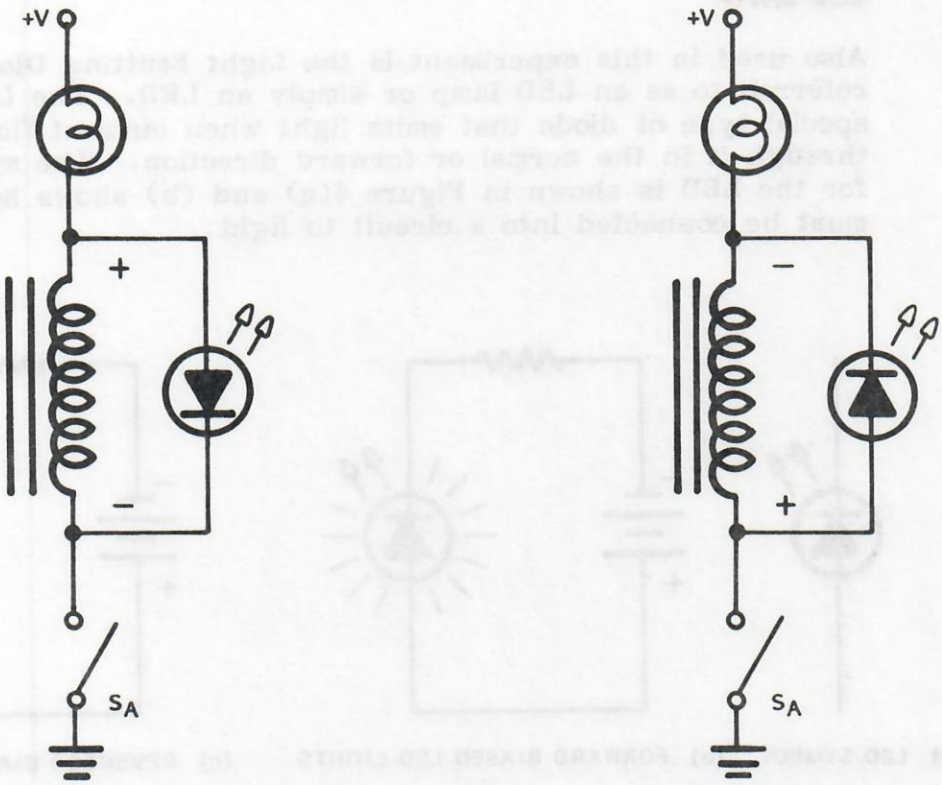


Figure 6 - LED Symbol and circuits.

The LED is used in this experiment to show the opposition to the initial flow of current when voltage is first applied to the inductor and again to show the polarity of the "inductive kick" voltage created when the voltage is removed. Figure 7(a) shows how to detect the coil voltage caused by the delayed ON current. Figure 7(b) shows how to detect the inductive pulse voltage that occurs when the current is stopped. Note that in (b) the LED polarity has been reversed.



LED BLINKS WHEN SA IS CLOSED

When SA is closed the coil will display a high opposition to the flow of current and all the current will flow through the LED which will blink on for a moment. The current eventually flows through the coil and the LED turns off.

(a) DELAYED ON CURRENT

LED BLINKS WHEN SA IS OPENED

When SA is opened the magnetic field collapses and induces a voltage of the polarity shown. With the LED wired as shown, it will blink for a moment each time SA is opened, indicating the presence of the induced voltage from the collapsing field.

(b) REVERSE VOLTAGE

Figure 7 - Use of an LED to show the voltage state across the inductor.

PROCEDURE

1. Plug in the CES 306 Transformer card making sure the pin 1 marking is on the top left hand side.

2. Wire the circuit shown in Figure 8.

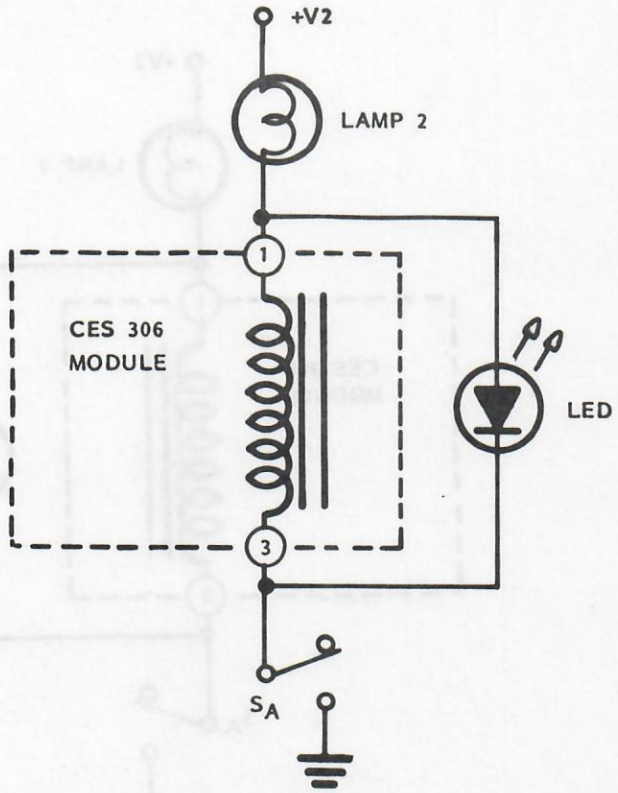


Figure 8 - Delayed current indicator circuit; EXPERIMENT.

4.1 DELAYED CURRENT AND CEMF

3. Set Switch SA to the UP position. Both Lamp 2 and the LED should be off and no current flows.

4. Watch the LED closely and then slowly move Switch SA DOWN to turn Lamp 2 ON.

   Place Switch SA UP again and then repeat this several times being sure to move SA slowly.

   What does the LED indicate and WHY?

4.2 INDUCED VOLTAGE (INDUCTIVE KICK)

5. Reverse the leads connected to the LED so that the new circuit is as shown in Figure 9.

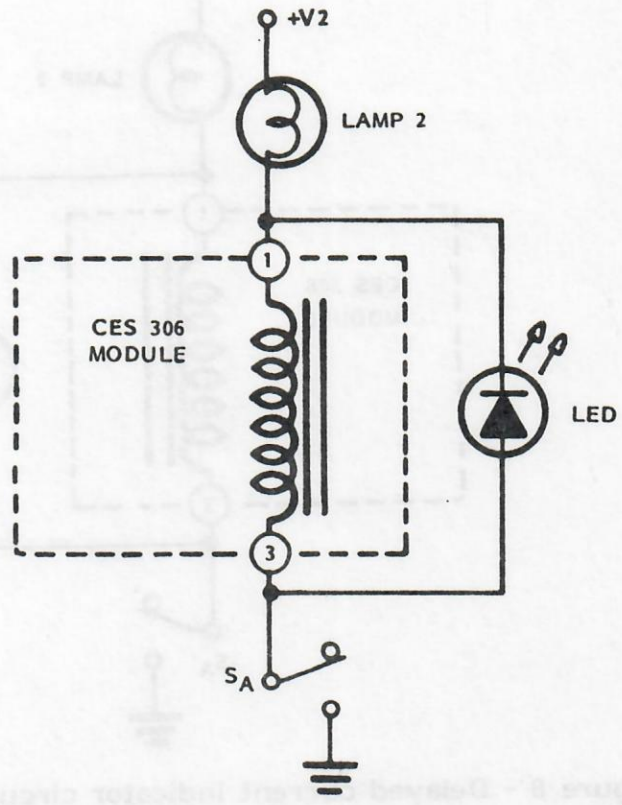


Figure 9 - Reverse voltage indicator circuit; EXPERIMENT.

6. Set Switch SA DOWN; Lamp 2 should be ON.

7. Watch the LED closely and slowly move Switch SA UP to cut off the current.

   Set Switch SA DOWN again and repeat this several times being sure to move SA slowly.

   What does the LED indicate and WHY?

4.3 BLOCKING AC, PASSING DC

8. Remove all previous wiring and wire the circuit shown in Figure 10 below.

   Set Switch SB UP so that the inductor is in series with the lamp.

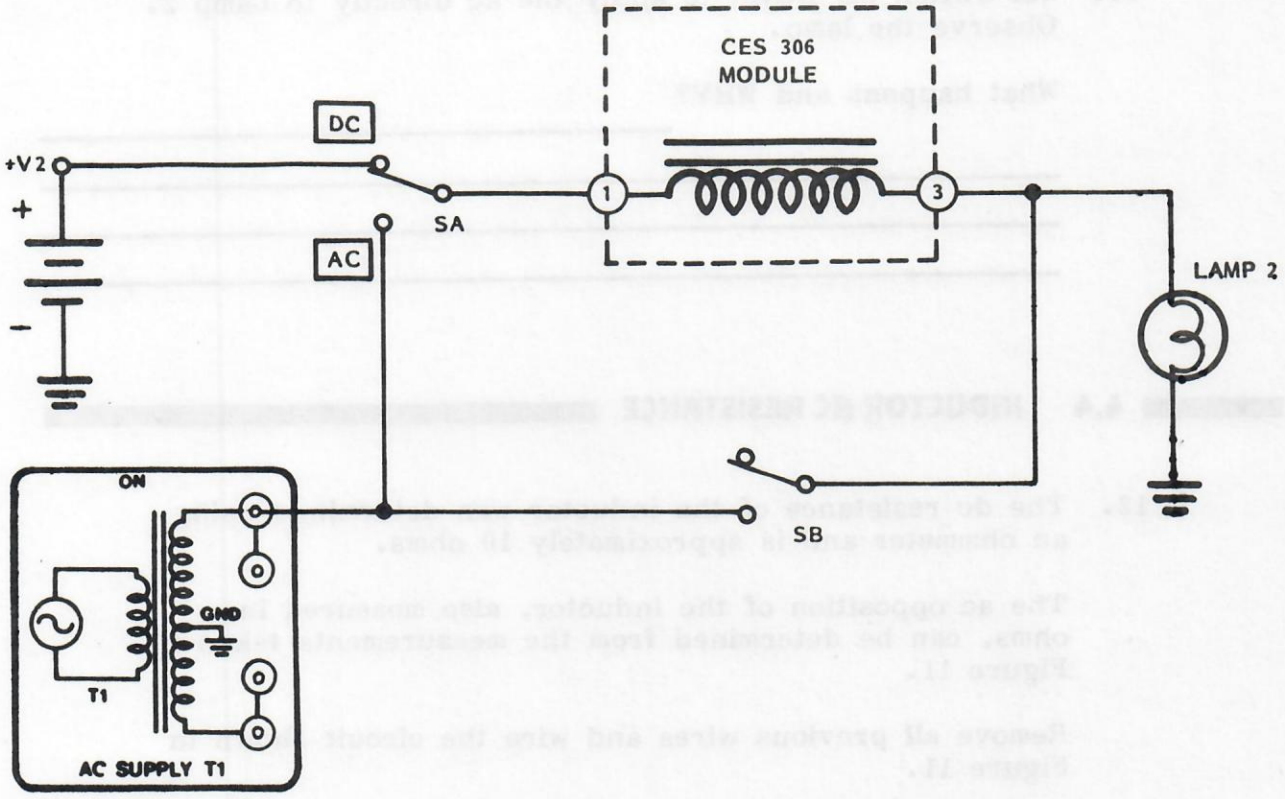


Figure 10 - Inductor series circuit EXPERIMENT.

9. Set Switch SA UP to apply a dc voltage that will permit a dc current flow. Observe LAMP 2.

What happens and WHY?

10. Set Switch SA DOWN to apply an ac voltage that will permit an ac current to flow. Observe Lamp 2.

What happens and WHY?

11. Set Switch SB DOWN to apply the ac directly to Lamp 2. Observe the lamp.

What happens and WHY?

4.4 INDUCTOR AC RESISTANCE

12. The dc resistance of the inductor was determined using an ohmmeter and is approximately 10 ohms.

The ac opposition of the inductor, also measured in ohms, can be determined from the measurements taken in Figure 11.

Remove all previous wires and wire the circuit shown in Figure 11.

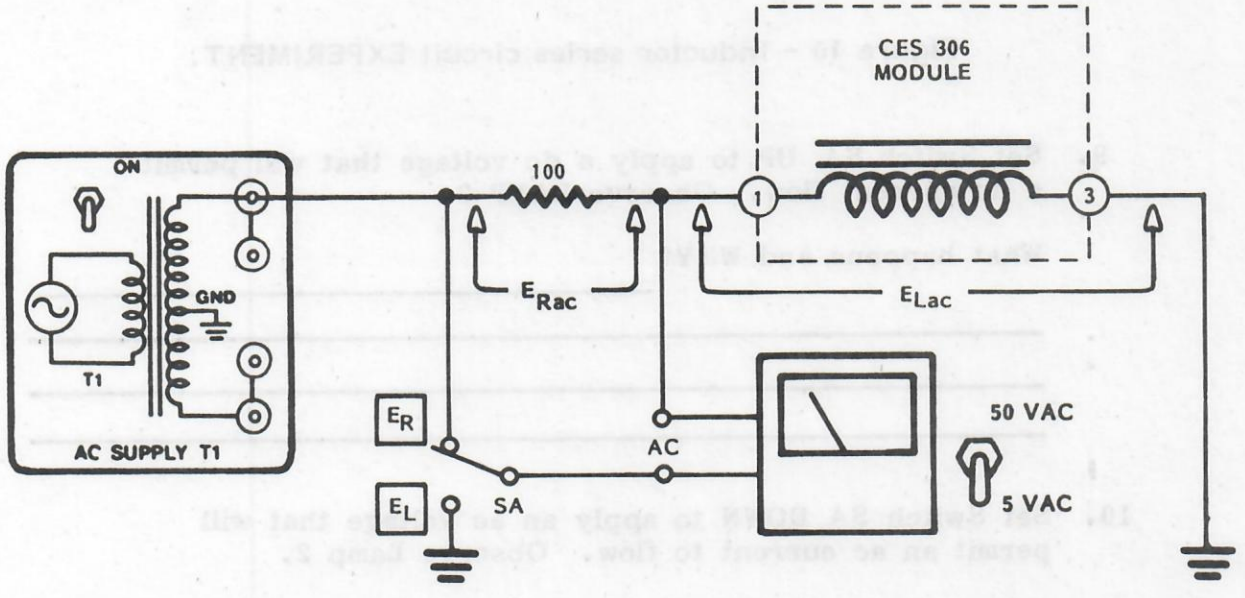


Figure 11 - Circuit to measure coil opposition to ac; EXPERIMENT.

13. Set the ac meter range switch DOWN to the 5 V range. Place Switch SA UP to measure the ac drop across the 100 ohm resistor.

Record the voltage below

E_{Rac} = _____ V

14. Move the ac meter voltage range switch UP to the 50 volt range.

Move Switch SA DOWN to now measure the ac voltage across the inductor and record the value below.

E_{Lac} = _____ V

15. Calculate the current flow in the circuit based on 100 ohms and the voltage drop across the 100 ohm resistor as measured in step 13.

$$I_{ac} = \frac{E_{Rac}}{R} = \frac{(\quad)}{100}$$

I_{ac} = _____ A

16. Calculate the ac resistance or inductive reactance, X_L, of the inductor based on the series circuit current and the voltage drop across the inductor.

$$\text{AC Resistance } X_L = \frac{E_{Lac}}{I_{Lac}} = \frac{(\quad)}{(\quad)}$$

X_L = _____ Ω

How does the ac opposition or inductive reactance, X_L, compare to the given dc resistance of 10 ohms? _____

_____

_____

The ac resistance X_L for inductors, will be covered in detail in Unit G3, Experiment No.1.

CONCLUSIONS

We have learned from this experiment that:

An inductor delays the rise of the current that flows through it.

When the current flow through an inductor is cut off, the magnetic field that exists around that inductor shrinks inward or collapses inward inducing a voltage in the coil. The voltage polarity is opposite to that used to create the field.

The voltage pulse developed by the shrinking field is often very much greater than the source voltage and is called the "inductive kick."

The coil develops an opposition to the flow of ac called Inductive Reactance or X_L.

A single transformer winding may be used as an inductor.

An LED lamp is a diode that emits light only when forward biased and when current flows through it.

ASSIGNMENT

Answer the following multiple choice questions.

1. When current flows through a wire:

   a. some heat is developed by the wire though small.
   b. a voltage drop occurs across the wire though small.
   c. a magnetic field is created around the wire though weak.
   d. all of the above.

2. By lengthening a current carrying wire and winding it in the form of a coil, the:

   a. heat developed decreases.
   b. voltage drop across the wire decreases.
   c. magnetic field strength increases.
   d. all of the above.

3. An inductor, when powered by dc, causes:

   a. a delay in the current rise.
   b. an inductive kick when the current is stopped.
   c. a dc opposition to current due to wire resistance.
   d. all of the above.

4. To increase the delay in the build-up of current through the inductor, it is necessary to:

   a. increase the applied voltage.
   b. remove turns from the inductor.
   c. add turns to the inductor.
   d. increase the circuit resistance but keep the number of coil turns constant.

5. Adding turns to an inductor will increase the:

   a. inductance by the square of the turns.
   b. delay in current rise.
   c. dc resistance of the coil.
   d. all of the above.

6. When the current flow through an inductor is cut off, the magnetic field:

   a. collapses generating a voltage of the same polarity as the voltage that created the field.
   b. shrinks to generate an inductive kick opposite in polarity to the voltage that created the field.
   c. expands outward and disappears.
   d. none of the above.

7. The opposition of the coil to the flow of ac through it is called:

   a. inductive reactance.
   b. capacitive reactance.
   c. inductive resistance.
   d. Y_L.

8. A 5 henry and a 20 henry inductor are placed in parallel. The effective inductance is:

   a. 25 H.
   b. 15 H.
   c. 4 H.
   d. 100 H.

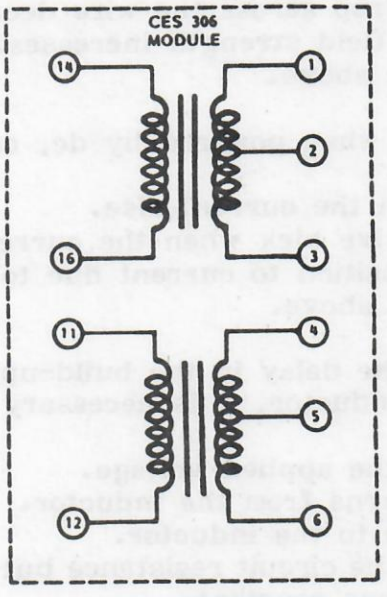


Figure 12 refers to question 9.

9. If the transformer winding shown in Figure 12 above has an inductance of 200 mH from terminal 1 to 3, the inductance from terminal 1 to 2 will be equal to:

   a. 200 mH.
   b. 100 mH.
   c. 50 mH.
   d. insufficient data.

10. An LED when connected to a source of 60 Hz ac voltage will:

   a. not light.
   b. light every half cycle but appear to be on continuously.
   c. burn out.
   d. incandesce.

KEY TERMS

1. INDUCTANCE

   The property of a component that opposes any change in the current flowing through it.

2. INDUCTIVE OPPOSITION (X)

   The action of an inductor that opposes the flow of ac through it. The opposition, called reactance, increases with frequency and inductance.

3. INDUCTIVE KICK

   The pulse of voltage that appears across an inductor when the current flow is broken suddenly. The voltage generated can be very much greater than the source voltage.

4. INDUCTIVE REACTANCE (X_L)

   The opposition to the flow of ac through an inductor. It is measured in ohms and indicated as X_L.

5. LIGHT EMITTING DIODE (LED)

   A special type of diode that emits light when forward biased.

Transformers

INFO SHEET 5

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Describe the construction of an iron core transformer.
2. Explain the use of tapped transformer windings.
3. Draw the symbols for various types of transformers.
4. Identify primary and secondary windings.
5. Calculate the transformer turns ratio.
6. Identify step-up and step-down transformers.
7. Calculate winding voltages and currents for a loaded transformer.
8. Identify transformer polarity using sense dots.
9. Define the causes of loss in transformers.
10. Calculate transformer efficiency.

DISCUSSION

A transformer is an electrical component that consists of two or more windings placed close to each other so that their magnetic fields are COUPLED. As shown in Figure 1, when an ac voltage is applied to one winding, called the PRIMARY, it creates a changing magnetic field that induces a voltage in the other winding, called the SECONDARY. It is generally desired that the coupling between the primary and secondary be very high so that all the flux lines from the primary are coupled to the secondary. In order to achieve this good coupling (close to 100% or k = 1), the transformers used for power and audio frequencies use an iron core such as shown in Figure 1.

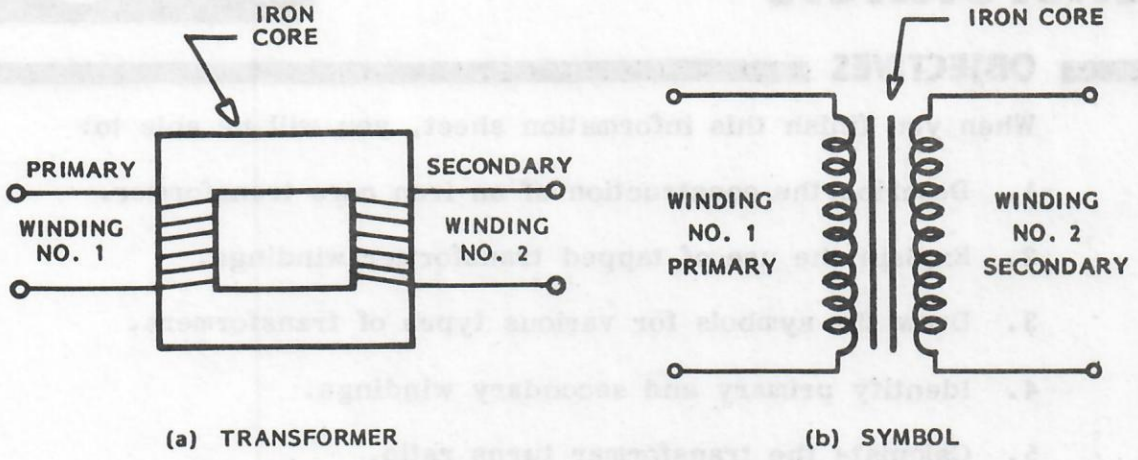


Figure 1(a) - Transformer construction and (b) its symbol.

The two windings are isolated from each other; that is, there is no wired connection between the two windings. The transformer will not pass dc but will pass ac voltages.

TURNS RATIO

Consider the transformer in Figure 2 with two windings, one primary winding (N_p) and one secondary winding (N_s) where N equals the number of turns on a winding.

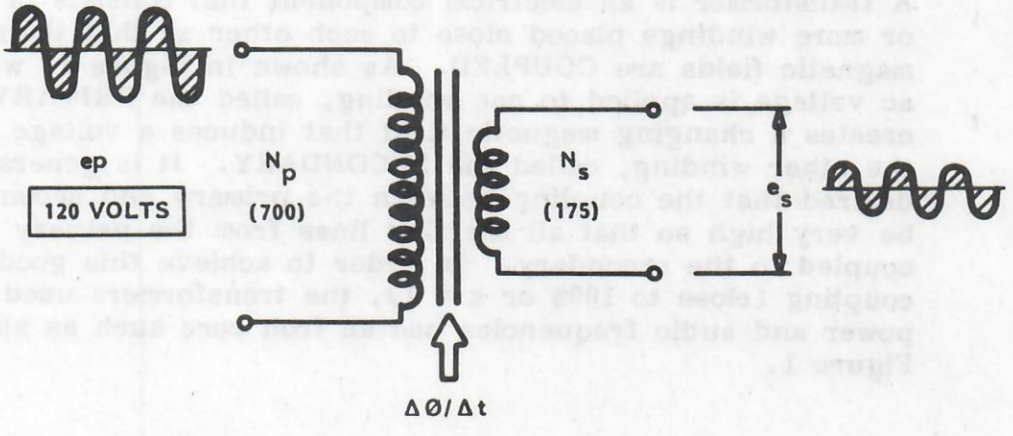


Figure 2 - Transformer turns ratio.

In Information Sheet 4, it was indicated that the equation relating ac voltage, e_{ind}, and flux change $\Delta\Phi$ in a given time, Δt, and the turns, N, is:

$$e_{ind} = N \frac{\Delta\Phi}{\Delta t} \qquad (1)$$

We can also write this equation as:

$$\frac{\Delta\Phi}{\Delta t} = \frac{e}{N} \qquad (2)$$

Writing this equation for the primary and secondary we get

$$\frac{\Delta\Phi}{\Delta t} = \frac{e_p}{N_p} \text{ and } \frac{\Delta\Phi}{\Delta t} = \frac{e_s}{N_s} \qquad (3)$$

Since $\Delta\Phi/\Delta t$ is the same in both the primary and secondary windings, then

$$\frac{e_s}{N_s} = \frac{e_p}{N_p} \qquad (4)$$

We can rewrite this equation to indicate the output voltage.

$$\boxed{e_s = \frac{N_s}{N_p} e_p} \qquad (5)$$

For example, in Figure 2

$N_p = 700$ t
$N_s = 175$ t
$e_p = 120$ Volts AC

The output or secondary voltage is:

$$e_s = \frac{N_s}{N_p} e_p$$

$$= \frac{175}{700} (120)$$

$$\boxed{e_s = 30 \text{ VOLTS AC}}$$

The turns ratio, TR, is written as some number to 1, in this case as 4:1. The number of turns drawn on the transformer schematic symbol does not indicate the actual number of turns. The turns ratio is defined as

TURNS RATIO	$TR = \frac{N_s}{N_p} = \frac{e_s}{e_p}$ (6)

In the example given, with a primary voltage of $e_p = 120$ V and a secondary voltage of $e_s = 30$ volts, the transformer is called a STEP-DOWN TRANSFORMER.

If the same transformer were used and the windings were reversed as shown in Figure 3, the output voltage would be higher than the input voltage. This is called a STEP-UP TRANSFORMER.

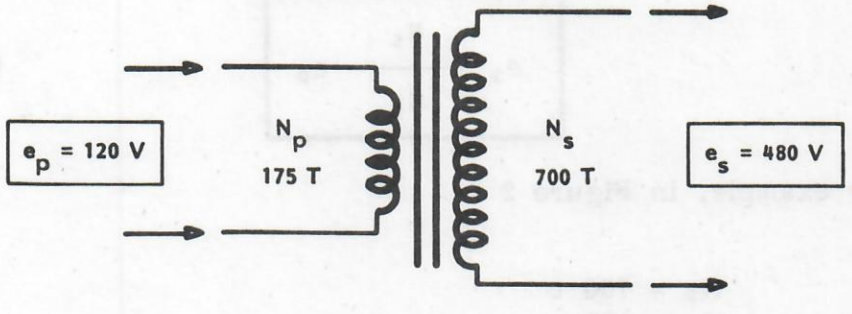


Figure 3 - Step-up transformer.

In the case illustrated in Figure 3, the output voltage is

$$e_s = \frac{N_s}{N_p} e_p$$

$$= \frac{700}{175} (120)$$

$$\boxed{e_s = 480 \text{ VOLTS AC}}$$

The transformer has a turns ratio of 1:4 calculated from

$$TR = \frac{N_p}{N_s}$$

$$= \frac{175}{400}$$

$$\boxed{TR = 1:4}$$

Another way of expressing the turns ratio of the transformer is to always state it as X:1 for either step-up or step-down. Thus, for the step-up transformer of our example, it would be expressed as:

TR = 4:1 Step-Up

For the step-down transformer, the turns-ratio would be expressed as:

TR = 4:1 Step-Down

THE IDEAL TRANSFORMER

In the perfect transformer, all of the magnetic lines of flux generated in the primary are transferred to the secondary and all the primary power and energy is also delivered to the secondary without any loss. There are, however, many power losses in a real transformer which are covered a little later. For now we will consider the performance of the perfect or ideal transformer. The factors to be considered are:

a. Voltage Transfer
b. Current Transfer
c. Load or Resistance Transfer

An ideal transformer is pictured below in Figure 4.

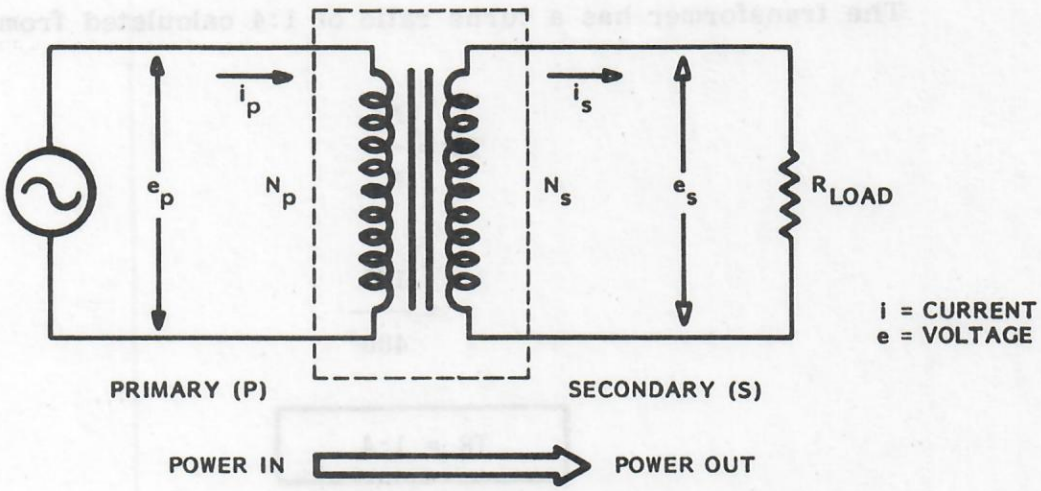


Figure 4 - The ideal transformer.

For the ideal transformer, shown in Figure 4, all of the input power, P_{in}, is transferred to the output. Thus

$$P_{out} = P_{in} \qquad (7)$$

Because power, P, equals e · i, then:

$$e_s \cdot i_s = e_p \cdot i_p \tag{8}$$

or

$$\frac{i_s}{i_p} = \frac{e_p}{e_s} \tag{9}$$

We showed earlier (equation 4) that:

VOLTAGE RATIO	$\frac{e_s}{e_p} = \frac{N_s}{N_p}$

(4)

From the above two equations, (4) and (9), we have:

CURRENT RATIO	$\frac{i_s}{i_p} = \frac{N_p}{N_s}$

(10)

INPUT RESISTANCE

The transformer primary voltage and current are defined as e_p and i_p. This means that the primary looks like a resistance, R_{IN}, to the input voltage source. Using Ohm's Law, the input resistance is:

$$R_{IN} = \frac{e_p}{i_p} \tag{11}$$

From equation (4) we can derive

$$e_p = \frac{e_s N_p}{N_s} \tag{12}$$

and from equation (10) we can derive

$$i_p = \frac{i_s N_s}{N_p} \qquad (13)$$

We can now write for the primary input resistance, R_{IN}, that

$$R_{IN} = \frac{e_p}{i_p} = \left(\frac{e_s N_p}{N_s}\right)\left(\frac{N_p}{i_s N_s}\right)$$

or:

$$R_{IN} = \frac{e_s}{i_s}\left(\frac{N_p}{N_s}\right)^2 \qquad (14)$$

Since

$$\frac{e_s}{i_s} = R_L$$

where R_L is the secondary load resistance in Figure 4, equation (14) may be rewritten as

$$\boxed{R_{IN} = R_L\left(\frac{N_p}{N_s}\right)^2} \qquad (15)$$

It may be seen then, that the secondary load resistance, R_L, appears to be a different resistance value at the input to the transformer.

EXAMPLES

Our earlier example of a step-down transformer is shown below in Figure 5.

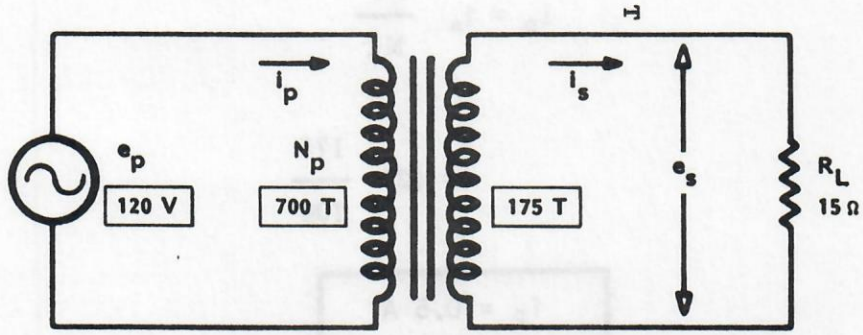


Figure 5 - The ideal transformer and circuit values.

a. The output or secondary voltage was calculated earlier as:

$$e_s = \frac{N_s}{N_p}(e_p) \qquad (5)$$

$$= \frac{175}{700}(120)$$

$$\boxed{e_s = 30 \text{ VOLTS}}$$

b. The output or secondary current is:

$$i_s = \frac{e_s}{R_L}$$

$$= \frac{30}{15}$$

$$\boxed{i_s = 2 \text{ A}}$$

c. The input or primary current is:

$$i_p = i_s \frac{N_s}{N_p} \qquad (13)$$

$$= (2) \frac{175}{700}$$

$$\boxed{i_p = 0.5 \text{ A}}$$

d. The input equivalent or "apparent" resistance can be calculated in two ways:

1)

$$R_{IN} = \frac{e_p}{i_p}$$

$$= \frac{120}{0.5}$$

$$\boxed{R_{IN} = 240 \text{ OHMS}}$$

2)

$$R_{IN} = R_L \left(\frac{N_p}{N_s}\right)^2$$

$$= 15 \left(\frac{700}{175}\right)^2$$

$$= (15)\ (4)^2 \quad = (15)\ (16)$$

$$\boxed{R_{IN} = 240 \text{ OHMS}}$$

The transformer can then be considered as a:

a. VOLTAGE TRANSFORMER (120 V input to 30 V output)
b. CURRENT TRANSFORMER (0.5 A input to 2 A output)
c. RESISTANCE TRANSFORMER (15 ohm output load appears as 240 ohms at the input)

TRANSFORMER WINDING VARIATIONS

Transformers can be made with multiple secondary windings and windings that are "tapped," that is, three or more connections on it. This is shown below in Figure 6.

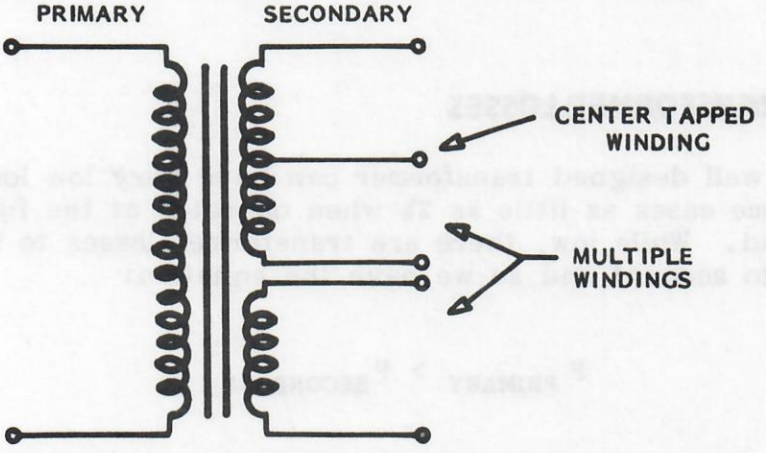
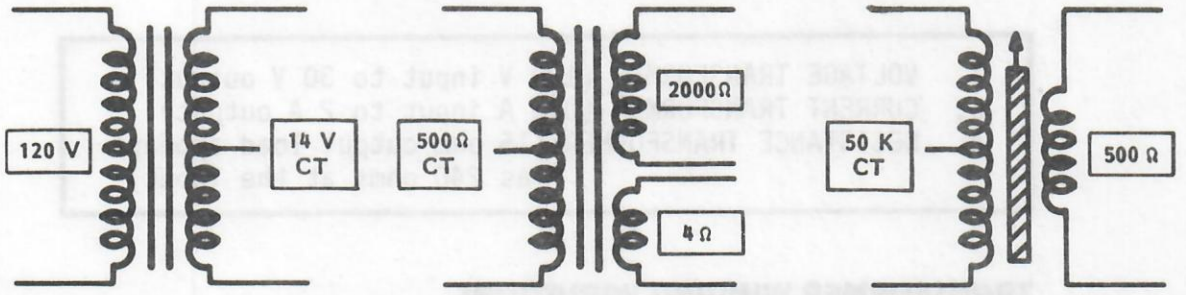


Figure 6 - Transformer winding variations.

TRANSFORMER NOMENCLATURE

Transformer characteristics can be specified in several ways. Consider three transformer types used with the Ed-Lab trainer. In the CES 306 Power Transformer Module the specifications are in terms of voltage transformation. For the CES Audio Transformer Module, the specifications are in terms of ac resistance transformation. The IF Transformers (intermediate frequency) on the CES Superheterodyne Module are also specified by ac resistances. All three are summarized in Figure 7 on the next page.



(a) CENTER TAPPED (CT) STEP-DOWN POWER TRANSFORMER CES 306

(b) THREE WINDING AUDIO TRANSFORMER CES 313

(c) TAPPED IF TRANSFORMER CES 301

Figure 7 - Specifications for three types of transformers.

TRANSFORMER LOSSES

A well designed transformer can have very low losses, in some cases as little as 2% when operated at the full design load. While low, there are transformer losses to be taken into account and so we have the equation:

$$P_{PRIMARY} > P_{SECONDARY} \qquad (16)$$

meaning that the primary power is greater than the secondary power in order to make up for any losses in the transformer.

Transformer power losses are caused by four factors. These are:

1. COPPER or I^2R LOSSES

   Each transformer winding has resistance due to the long length of wire used for the coil. To keep the resistance as low as possible the largest diameter wire is used that is reasonable for the current capacity of the transformer. The power loss is I^2R and occurs in the form of heat. The higher the I^2R losses the hotter the transformer will get when operating.

2. EDDY CURRENTS

   Looking back at the iron core of the transformer shown in Figure 1, it is possible to visualize this iron core as a single turn closed loop secondary with a very low resistance. The core is like a winding and there is a high core current. This current, called an Eddy current, serves only to heat the core and waste power.

Eddy currents are reduced by constructing the core using layers of iron, called LAMINATIONS, instead of solid metal. This method of construction results in a higher core resistance and less power loss. Laminations will be discussed later in this information sheet on page 16.

3. HYSTERESIS

Each time the polarity of the voltage applied to the primary changes, the iron core material's magnetic dipoles have to realign in the direction of the new field polarity. The energy and power needed for this realignment of the dipoles must come from the primary power. The constant shifting of the core dipoles also generates heat in the core.

4. FLUX LEAKAGE

All the lines of force generated by the primary do not reach the secondary. The lost lines of force will be absorbed by the surrounding metal surfaces. The energy needed to magnetize these metal surfaces must come from the primary. Flux leakage is minimized by winding the primary and secondary coils interleaved or on top of each other as shown later in Figure 8 on page 16.

TRANSFORMER EFFICIENCY

The total power lost in a transformer is due to the sum of the losses from Winding Resistance (I^2R), Eddy Currents, Hysteresis and Flux Losses. The greater the total loss, the less efficient the transformer. The efficiency of a transformer is rated in percentage and is calculated from:

$$\% \text{ Efficiency} = \frac{P_{OUT}}{P_{IN}} \times 100 \qquad (17)$$

For example, if a transformer primary winding draws 140 watts from its power source and the secondary delivers 133 watts to its load, the transformer efficiency is:

$$\% \text{ Efficiency} = \frac{P_{OUT}}{P_{IN}} \times 100$$

$$= \frac{133}{140} \times 100$$

$$\% \text{ Efficiency} = 95\%$$

Thus, 5% of the power drawn by the primary is lost to the copper resistance (I^2R), Eddy currents, hysteresis and lines of flux that fail to couple to the secondary.

CURRENT RELATIONSHIPS

Recall the following relationships between the transformer primary and secondary winding for an "ideal transformer" with 100% efficiency, given earlier.

$$P_{PRIMARY} = P_{SECONDARY} \qquad (7)$$

This expands to:

$$e_p\, i_p = e_s\, i_s \qquad (7a)$$

and as shown earlier can be transposed to

$$\boxed{\frac{e_p}{e_s} = \frac{i_s}{i_p}} \qquad (9)$$

Transposing equation (9) above to solve for i_p and i_s, we have:

$$\boxed{i_p = \frac{e_s}{e_p}\, i_s} \qquad (18)$$

and

$$\boxed{i_s = \frac{e_p}{e_s}\, i_p} \qquad (19)$$

For example, find the primary current, i_p, given the following and considering an ideal no-loss transformer.

$e_p = 120$ V; $e_s = 100$ V; $i_s = 0.1$A

$$i_p = \frac{e_s}{e_p} i_s$$

$$= \frac{100}{120} (0.1)$$

$$\boxed{i_p = 0.083 \text{ A}}$$

This produces a primary power of:

$$P_p = e_p \cdot i_p$$

$$= (120)(0.083)$$

$$\boxed{P_p = 10 \text{ WATTS}}$$

The secondary power dissipation is:

$$P_s = e_s \cdot i_s$$

$$= (100)(0.1)$$

$$\boxed{P_s = 10 \text{ WATTS}}$$

TRANSFORMER CONSTRUCTION

A most frequently used construction method for power transformers and audio transformers is shown in Figure 8(a). The primary winding is wound on a phenolic form. A layer of insulating material is placed over the primary and the secondary is wound on top of the primary.

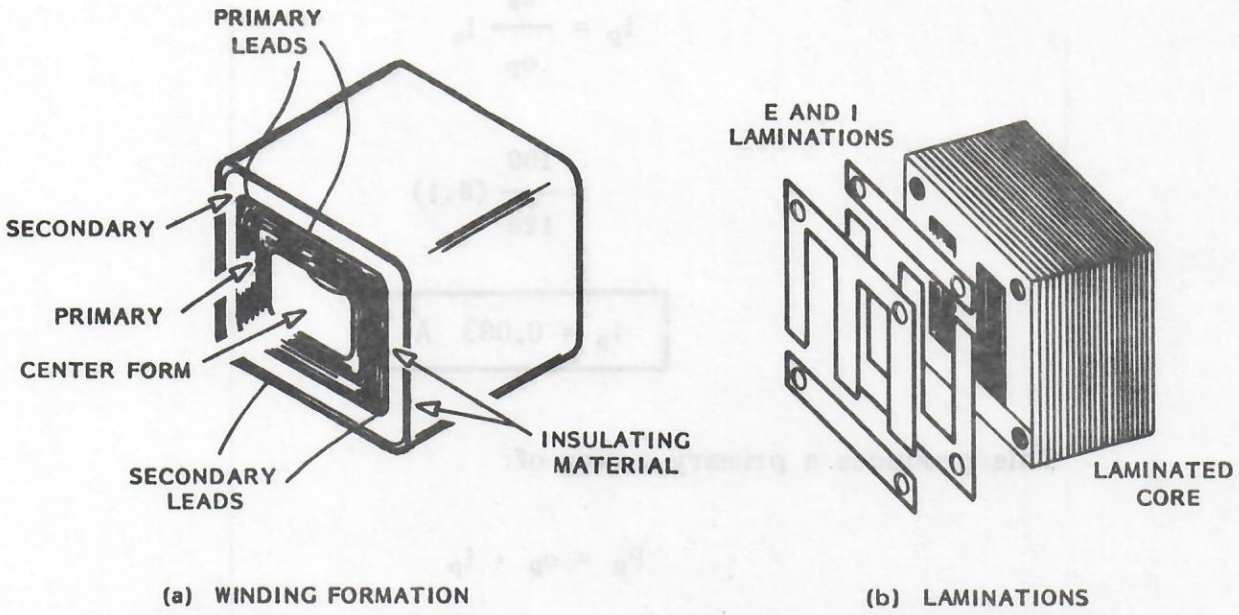


Figure 8 - Transformer construction.

After the coils are wound as shown in Figure 8(a), the core is assembled in the windings for a complete transformer. The core is made up of layers of steel or iron. Each layer, called a LAMINATION, is insulated from the next lamination by an oxide coating or a layer of varnish.

The laminations are stacked in reverse order and then either bolted together or clamped together by a metal frame as shown in Figure 9.

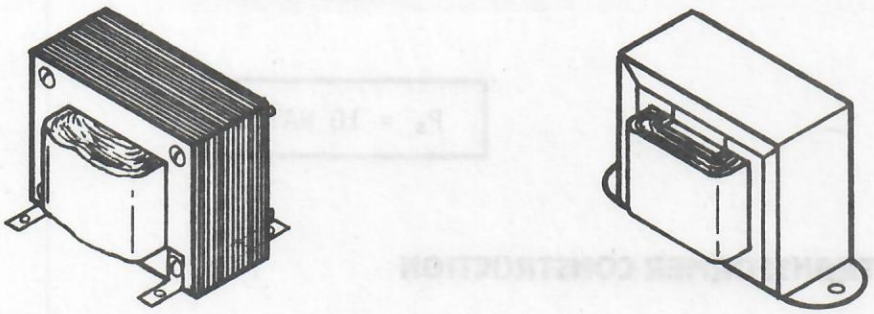
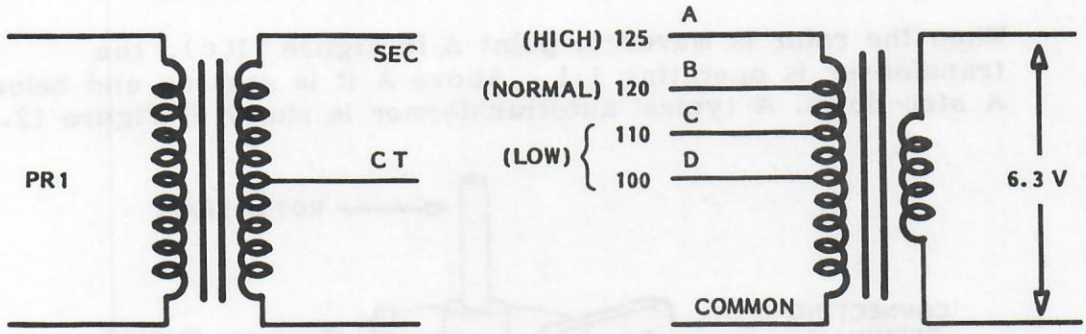


Figure 9 - Methods of securing transformer laminations.

TRANSFORMER TYPES

Transformers may have windings with one or more taps. The CES 306 Transformer module uses two transformers with center-tapped secondaries as shown below in Figure 10(a). A center tap provides an equal voltage on each half of the winding.



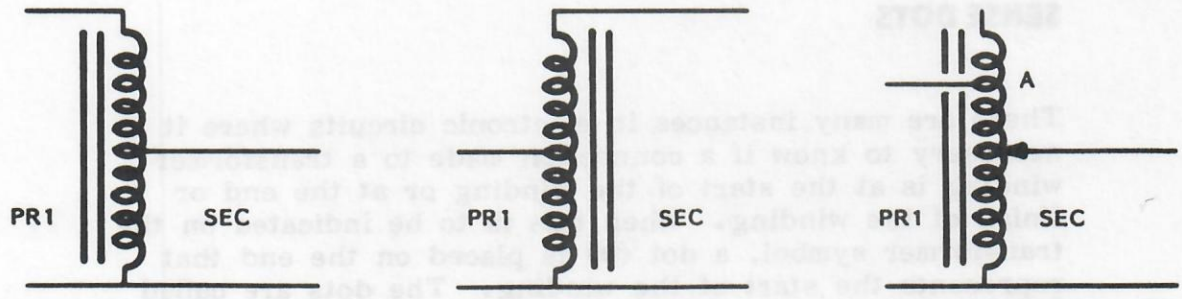
(a) CENTER-TAPPED SECONDARY (b) COMMON TAPPED PRIMARY

Figure 10 - Tapped transformer windings.

Figure 10(b) illustrates a tapped primary that is used to adjust for the available line voltage. The normal power line voltage is 120 and the transformer is designed to deliver 6.3 volts at the secondary. If the line voltage is 125 volts and the same primary is used, the output voltage will be slightly under 6.6 volts. To compensate for this, the power line is connected between common and 125. The added primary turns will adjust the turns ratio to produce 6.3 volts for 125 volts. Similarly, low power line voltages require connection to C or D to correct the turns ratio for a 6.3 volt output.

AUTOTRANSFORMERS

An AUTOTRANSFORMER is capable of step-up or step-down action but has a single winding. This is shown in Figure 11.



(a) STEP-DOWN (b) STEP-UP (c) VARIABLE

Figure 11 - Autotransformer configurations.

Figure 11(a) is a step-down transformer because the secondary has fewer turns than the primary. Figure 11(b) is a step-up transformer because the secondary has more turns than the primary. Figure 11(c) is the symbol used to indicate a variable autotransformer very often called a VARIAC which is a General Radio company trademark.

When the rotor is moved to point A in Figure 11(c), the transformer is operating 1:1. Above A it is step-up and below A step-down. A typical autotransformer is shown if Figure 12.

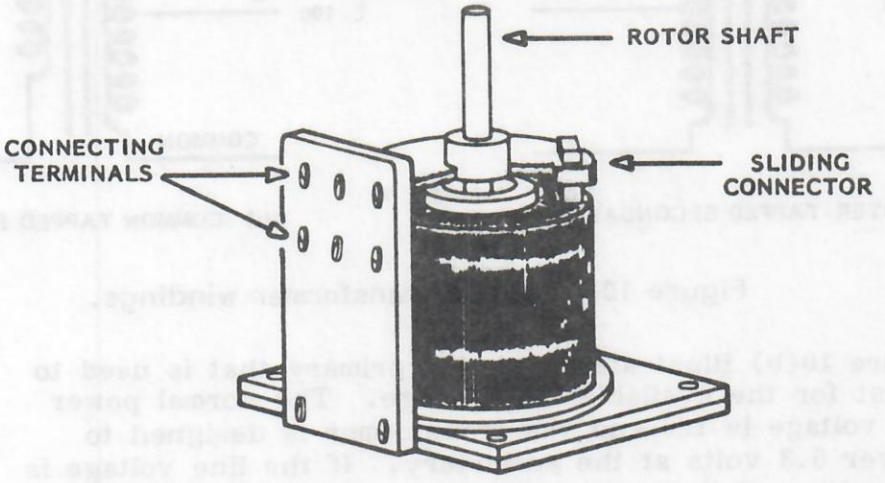


Figure 12 - Typical variable autotransformer.

The autotransformer has no special advantage over the conventional transformer except cost and weight reduction. It has, however, one major disadvantage in that the secondary is not electrically isolated from the primary. The autotransformer is most frequently used as the variable transformer shown in Figures 11(c) and 12. The output voltage is continuously variable from zero to 130 volts for an input of 120 volts.

SENSE DOTS

There are many instances in electronic circuits where it is necessary to know if a connection made to a transformer winding is at the start of the winding or at the end or finish of the winding. When this is to be indicated on the transformer symbol, a dot (●) is placed on the end that represents the start of the winding. The dots are called SENSE DOTS and are shown in Figure 13 on a transformer with two secondary windings.

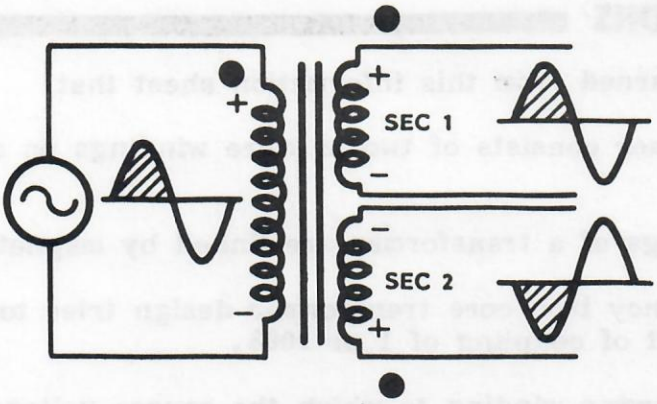


Figure 13 - Use of sense dots to indicate the winding starting point or common polarity signals.

The sense dots in Figure 13 indicate that when the dot end of the primary is positive, the dot end of each of the secondary windings will also be positive. Similarly, a negative polarity at the primary dot end will produce a negative polarity at the dot end of each secondary.

CONCLUSIONS

We have learned from this information sheet that:

A transformer consists of two or more windings on a common iron core.

The windings of a transformer are linked by magnetic flux.

Low frequency iron core transformer design tries to achieve a coefficient of coupling of 1 or 100%.

The transformer winding to which the source voltage is applied is called the primary.

Transformer windings from which output voltages are taken are called secondary windings.

A transformer can have more than one secondary winding.

Transformer primary and secondary windings may have various taps on them.

The primary and secondary windings of a transformer are electrically isolated from each other.

A transformer may step the primary voltage up or down depending upon the Turns Ratio.

Transformer windings, in schematics, are sometimes marked with sense dots to indicate instantaneous polarities.

Increasing the secondary current drain increases the primary current drain.

Transformer losses are due to copper losses, Eddy currents, hysteresis and lost flux lines.

Transformers operate at efficiencies of 75% to 98%.

Low frequency transformer cores are laminated to reduce Eddy current losses.

Auto transformers can be constructed so that they are variable.

Autotransformers do not have isolation from input to output.

ASSIGNMENT

Answer the following True-False questions.

1. A transformer consists of two or more windings that are coupled by magnetic lines of force. _____

2. A transformer is designed to attain a coefficient of coupling of 1. _____

3. The primary winding of a transformer is used to deliver power to a load connected across the primary wires. _____

4. The transformer primary winding transfers power to the secondary winding without a direct electrical connection. _____

5. The Turns Ratio of a transformer can be computed from $TR = N_s / N_p$. _____

6. A transformer with a TR of 5:1 step-up has 200 volts applied to the primary and will deliver 40 volts to the secondary. _____

7. A transformer with a TR of 4:1 step-down will deliver 30 volts from its secondary when 120 volts is applied to the primary. _____

8. Given a secondary voltage of 300 volts, a primary winding of 150 turns and a secondary of 600 turns, the primary voltage must be 125 volts. _____

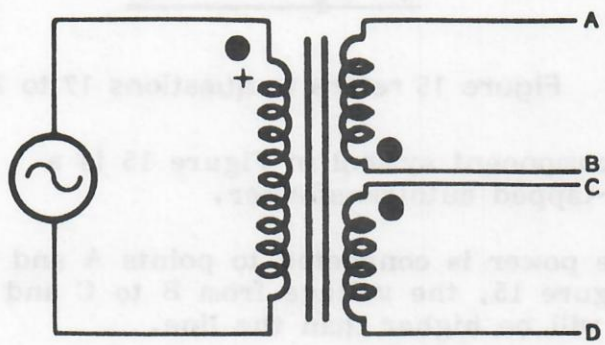


Figure 14 above refers to question 9.

9. The polarity, for the instant shown in Figure 9, is A-; B+; C-; D+. _____

10. The power distribution in an ideal transformer with 3 secondary windings is $P_{pr} = P_{sec\ 1} + P_{sec\ 2} + P_{sec\ 3}$. ____

11. As the secondary current load is increased the primary current also increases. ____

12. As the secondary load current is increased the transformer gets hotter due to increased Eddy currents in the core. ____

13. Hysteresis losses are due to small circulating currents in the transformer core. ____

14. The effects of Eddy currents in the transformer core can be corrected by using silicon steel instead of soft iron, ____

15. E-I laminations are used to assemble a core around a transformer winding. ____

16. A tapped primary winding can be used to adjust for higher or lower primary voltages. ____

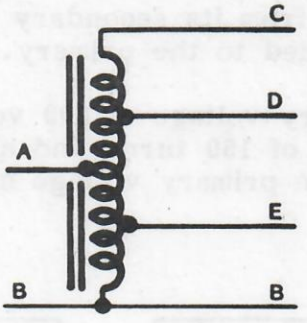


Figure 15 refers to questions 17 to 20.

17. The component symbol in Figure 15 is a multi-tapped autotransformer. ____

18. If the power is connected to points A and B in Figure 15, the voltage from B to C and B to D will be higher than the line. ____

Perform the following computations.

19. Winding AB in Figure 15 has 500 turns and winding BC has 600 turns. What is the voltage from BC given an input of 120 volts.

20. In Figure 15, winding AB has 500 turns and winding BE has 125 turns. Find the primary voltage given an output of 30 volts from BE.

KEY TERMS

1. AUTOTRANSFORMER

   A transformer with a single winding in which part of the winding acts as the primary and part as the secondary.

2. CENTER TAP

   A connection at the exact electrical center of a transformer winding or resistor network.

3. COEFFICIENT OF COUPLING

   The degree of magnetic coupling between two windings.

4. CORE

   A form on which transformers and inductors are wound.

5. EDDY CURRENTS

   Currents induced in the transformer core by the magnetic field developed by the primary winding.

6. HYSTERESIS

   The lag in the magnetization of the transformer core material because of the molecule friction generated by the magnetic dipoles.

7. LAMINATED CORE

   A core made of layers of iron or steel each insulated from the next by an oxide or varnish coating.

8. PRIMARY WINDING

   The transformer winding through which the source current flows to create a magnetic field that will induce a voltage in the secondaries.

9. SECONDARY WINDING

   The transformer winding from which the output is taken

10. SENSE DOTS

    Markings on the transformer symbol that indicate the start of windings.

11. STEP-DOWN TRANSFORMER

A transformer whose secondary output voltage is lower than the primary input voltage.

12. STEP-UP TRANSFORMER

A transformer whose secondary output voltage is higher than the primary input voltage.

13. TAP

A permanent electrical connection on a transformer winding somewhere between the two ends of that winding.

14. TRANSFORMER

A transformer consists of two or more windings on a common iron core which can transfer electrical energy from one winding to another by magnetic coupling.

15. TURNS RATIO

The ratio on the number of turns on the primary winding to the number of turns on the secondary winding.

Transformer Action 5

OBJECTIVES

When you finish this experiment, you will be able to:

1. Calculate the turns ratio of a transformer.
2. Determine the voltage ratio of a transformer.
3. Calculate the input and output power of a transformer.
4. Determine the efficiency of a transformer.
5. Operate a transformer in the autotransformer configuration.

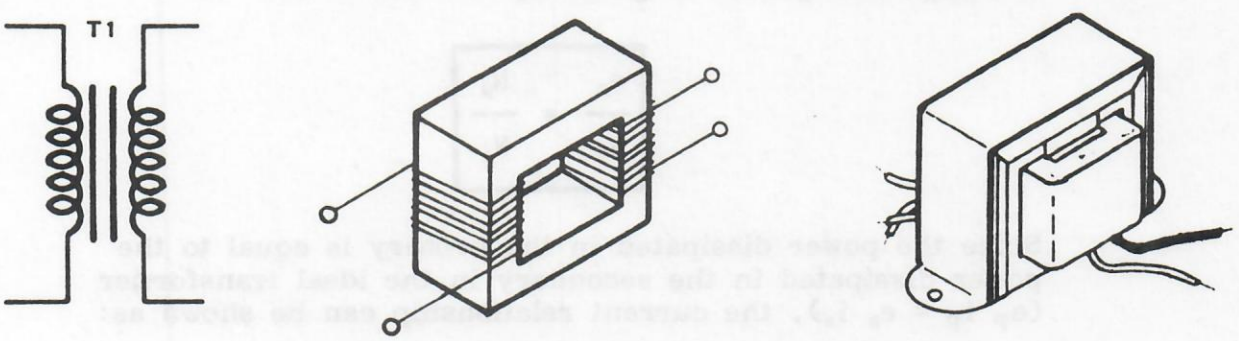
ADDITIONAL EQUIPMENT

a. CES 306 Power Transformer Module
b. Digital Multimeter (Optional)

DESCRIPTION

The construction and operation of the TRANSFORMER was described earlier in Information Sheet 5 as two coils wound on a common iron core. The ac voltage connected to the input coil (primary winding) generates a changing magnetic field and this changing magnetic field generates a changing voltage in the output coil (the secondary winding).

Figure 1 shows the transformer circuit symbol, its letter designation, its construction and appearance.



(a) IRON CORE TRANSFORMER SYMBOL

(b) BASIC TRANSFORMER CONSTRUCTION

(c) PHYSICAL APPERANCE OF TYPICAL TRANSFORMER

Figure 1 - Transformer symbol (a), basic construction (b), and appearance (c).

TRANSFORMER RELATIONSHIPS

The transformer is shown in Figure 2 labeled with the input and output voltages, input and output current and the turns designations. The mathematical relationships that follow are for an ideal transformer, that is, one that has no losses.

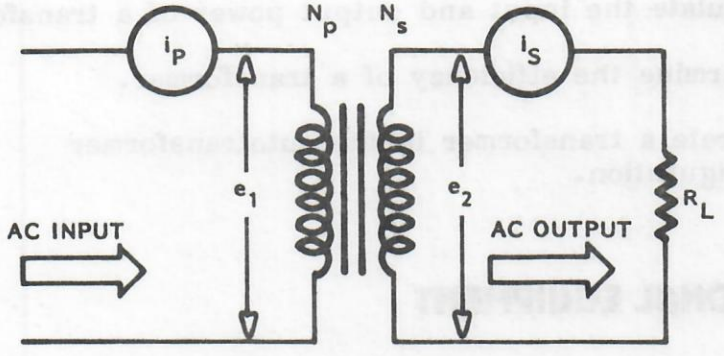


Figure 2 - Transformer circuit parameters.

The turns ratio, TR, between the primary and secondary windings in Figure 2 is determined from:

$$TR = \frac{N_p}{N_s}$$

where N_p = number of primary turns
N_s = number of secondary turns

The voltage relationship between the primary and secondary windings in Figure 2 is given by:

$$\frac{e_p}{e_s} = \frac{N_p}{N_s}$$

Since the power dissipated in the primary is equal to the power dissipated in the secondary in the ideal transformer ($e_p\ i_p = e_s\ i_s$), the current relationship can be shown as:

$$\frac{i_s}{i_p} = \frac{N_p}{N_s}$$

TRANSFORMER EFFICIENCY

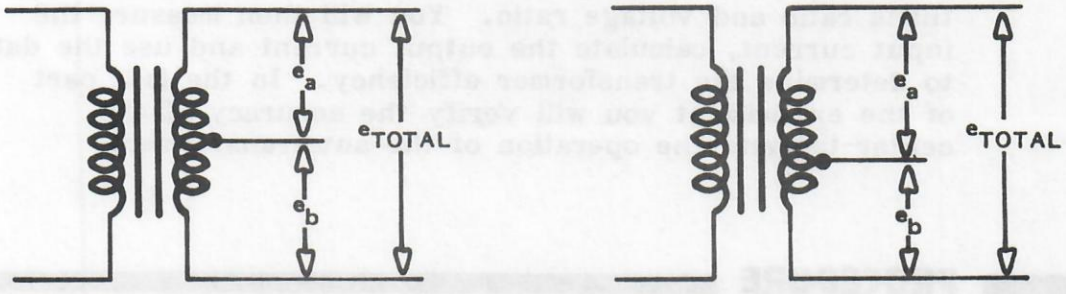
The transformer calculations outlined above are based on an efficiency of 100%, that is, no losses. You know, however, that there are I^2R losses due to wire resistance and losses in the core due to Eddy currents and Hysteresis and Flux Leakage. Because in most instances, these losses are low, they can be disregarded. The actual efficiency of the transformer is calculated from:

$$\% \text{ Efficiency} = \frac{P_{OUT}}{P_{IN}} \times 100$$

The power output in a real transformer will normally be less than the power input and so the efficiency will be under 100%. Efficiencies of 98% in large transformers designed to handle high power are not usual. In smaller transformers the efficiency can be 80% or less.

WINDING TAPS

Many transformer windings are TAPPED, that is they have more than two connections. Most frequently the tap is in the center of the winding as shown in Figure 3(a). This means that the output voltage e_a is equal to e_b and the total output will be equal to $2e_a$ (or $2e_b$).



$e_a = e_b$
$e_T = 2\,e_a$

(a) CENTER TAPPED WINDING

$e_a \neq e_b$
$e_T = e_a + e_b$

(b) TAPPED WINDING

Figure 3 - Tapped transformer windings.

The tapped winding in Figure 3(b) is off center and, as shown, the bottom portion of the winding, having fewer turns, will have less voltage than e_a. The total voltage, however is still equal to $e_a + e_b$.

AUTOTRANSFORMERS

The AUTOTRANSFORMER has a single winding that serves as both the primary and secondary and can act as a step-up or step-down device. Two autotransformers are shown in Figure 4.

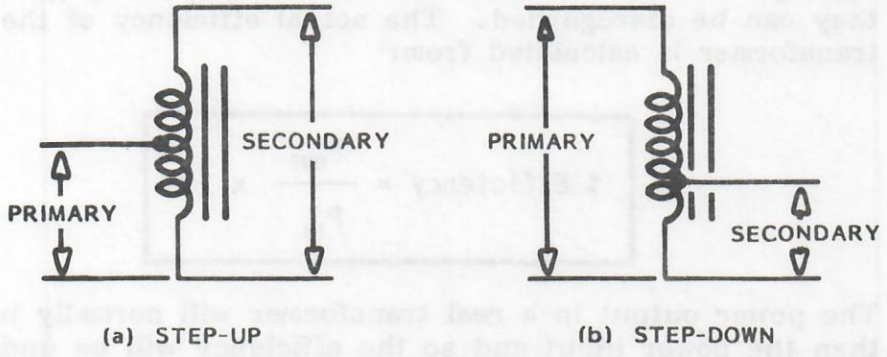


Figure 4 - Step-up and step-down autotransformers.

Note that the autotransformer does not provide electrical isolation between primary and secondary and thus is not suitable for some applications.

The relationship between the input and output voltages and the number of primary and secondary turns is the same as for the conventional transformer.

In this experiment, you will first test the step-up and step-down action of a power transformer and calculate the turns ratio and voltage ratio. You will then measure the input current, calculate the output current and use the data to determine the transformer efficiency. In the last part of the experiment you will verify the accuracy of the center-tap and the operation of the autotransformer.

PROCEDURE

1. Plug the CES 306 Power Transformer module into the Ed-Lab PC socket with Pin 1 positioned at the upper left.

5.1 STEP-UP TRANSFORMER

2. Wire the circuit shown in Figure 5.

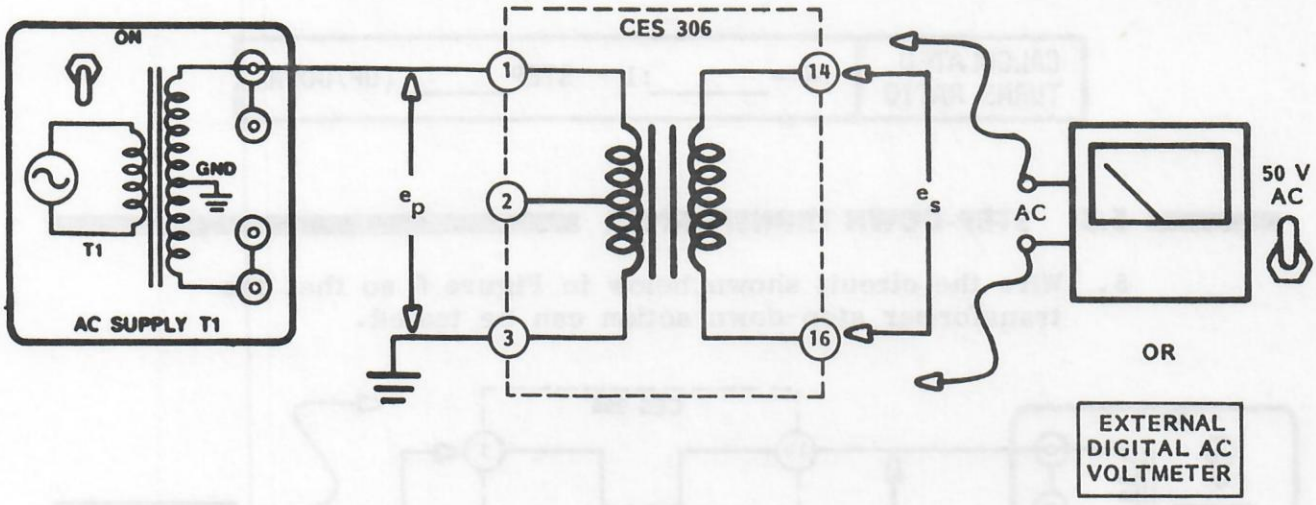


Figure 5 - Step-up turns ratio measurements; EXPERIMENT.

3. You may use the Analog meter on the Ed-Lab panel (0-50 VAC) or you can use an external Digital Multimeter for more accurate results.

   Read the input and output voltages on the transformer as shown in Figure 5 and record them below.

   Meter used (check one) ANALOG ☐ DIGITAL ☐

e_p = _____ V
e_s = _____ V

   Is the transformer wired as a step-up or step-down device?

   _____

5.2 TURNS RATIO

4. Calculate the turns ratio from:

$$TR = \frac{e_s}{e_p}$$

$$TR = \frac{(\quad)}{(\quad)}$$

CALCULATED TURNS RATIO	TR = _____:1 STEP _____(UP/DOWN)

5.3 STEP-DOWN TRANSFORMER

5. Wire the circuit shown below in Figure 6 so that the transformer step-down action can be tested.

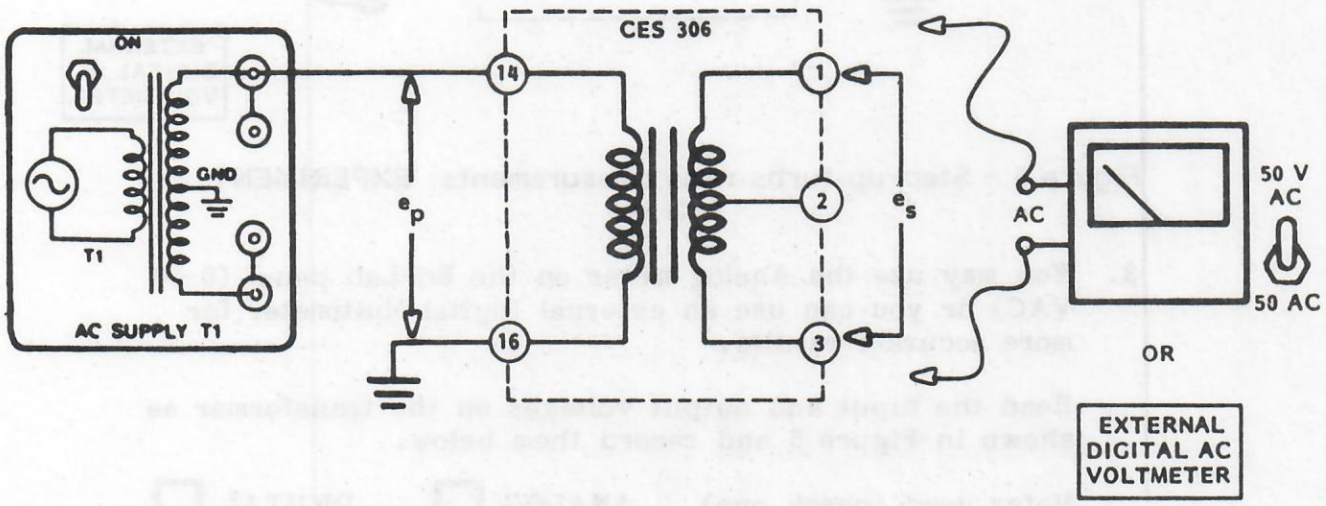


Figure 6 - Step-down turns ratio measurements; EXPERIMENT.

6. Use the Analog panel meter or an external Digital Multimeter and measure the primary and secondary voltages shown in Figure 6.

e_p = _____ V
e_s = _____ V

7. Calculate the turns ratio from:

$$TR = \frac{e_p}{e_s}$$

$$TR = \frac{(\quad)}{(\quad)}$$

CALCULATED TURNS RATIO	TR = _____:1 STEP_____(UP/DOWN)

The TR calculated above should be the same or close to the TR calculated earlier in step 4. Any difference is due to errors in reading the meter. On the 50 volt scale of the panel meter we can read in 1 volt increments only.

5.4 VOLTAGE RATIO

8. The turns ratio calculated in steps 4 and 7 is one of the means used to specify a transformer rating. Most transformers used to step ac up or down (usually called POWER TRANSFORMERS) have a primary input of 115 to 120 volts ac from the power line. The transformers are not specified by their turns ratio but by their voltage ratings. Typical standard transformer voltage ratings are specified as

120 V to 6 V
120 V to 12 V
120 V to 24 V
120 V to 48 V

Considering the turns ratio of the transformer calculated, which voltage ratio do you think corresponds to the transformer on the CES 306 Power Transformer Module?

VOLTAGE RATING	120 V to_____V

5.5 POWER LOSS AND EFFICIENCY

NO-LOAD INPUT CURRENT AND POWER

9. Wire the circuit shown below in Figure 7. The 100 ohm resistor, R_A, is wired in series with the primary so that the ac input current can be measured. This is done by measuring the voltage drop across R_A and using Ohm's Law.

Note that in this portion of the experiment the full ac supply voltage from T1 is used.

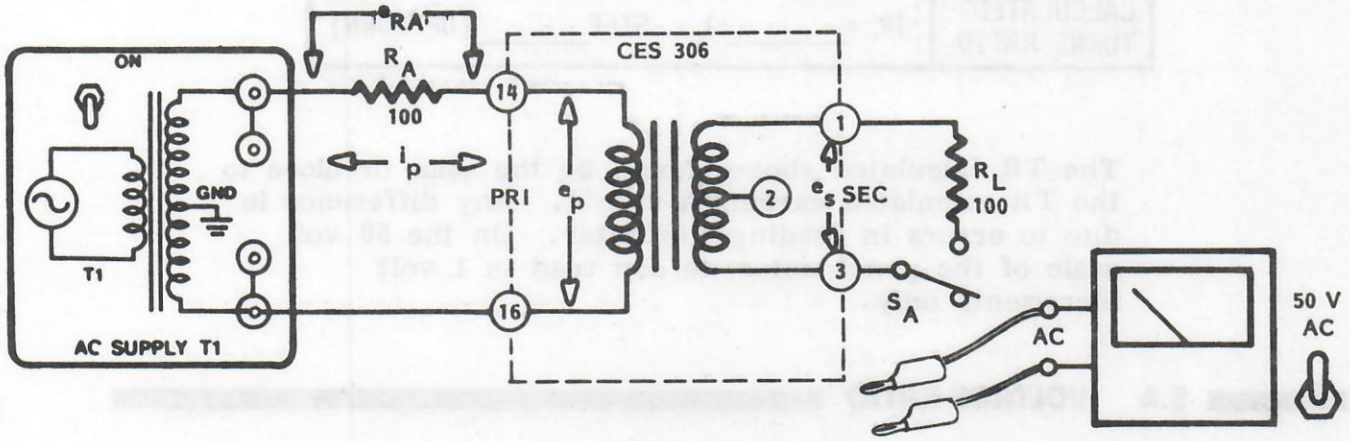


Figure 7 - Loaded step-down transformer EXPERIMENT.

10. Set Switch SA DOWN so that R_L is out of the circuit.

Measure the voltages listed below and record the values.

e_p =	V
e_s =	V
RA =	V

NO-LOAD VOLTAGES

11. The input or primary current is given by Ohm's Law as:

$$I = \frac{E}{R}$$

$$I_p = \frac{e_{RA}}{R_A} = \frac{(\quad)}{(100)}$$

PRIMARY CURRENT	I_p = A

12. The input power, P_{IN} or P_{PRI}, is given by:

$$P = e \cdot i$$

$$P_{IN} = e_p \cdot i_p = (\quad)(\quad)$$

MEASURED INPUT POWER	P_{IN} = _____ W

Since there is no output power (Switch SA is OPEN) all of the power is dissipated or lost in the transformer.

5.6 TRANSFORMER EFFICIENCY

13. Set Switch SA UP to connect the 100 ohm load across the secondary.

Measure the voltages listed below and record the values.

e_p = _____ V
e_s = _____ V
e_{RA} = _____ V

LOADED VOLTAGES

14. Calculate the input current using the measurements taken in step 13 above.

$$i_p = \frac{e_{RA}}{R_A} = \frac{(\quad)}{(100)}$$

INPUT CURRENT	i_p = _____ A

15. Calculate the Input and Output Power.

INPUT POWER:

$$P_p = e_p \cdot i_p = (\quad)(\quad)$$

(Use e_p from step 13 above.)
(Use i_p from step 14 above.)

INPUT POWER	P_{IN} = _____ W or _____ mW

OUTPUT POWER:

$$P = \frac{E^2}{R}$$

$$P_S = \frac{e_s^2}{R_L} = \frac{e_s^2}{100} = \frac{(\quad)^2}{100}$$

(Use e_s from step 13 above.)

OUTPUT POWER	P_{OUT} = _____ W or _____ mW

16. Calculate the power "lost" in the transformer.

$$P_{LOSS} = P_{IN} - P_{OUT}$$

$$= (\quad) - (\quad)$$

P_{LOSS} = _____ mW

List three possible causes for this power loss.

1. _____

2. _____

3. _____

17. Calculate the transformer efficiency from:

$$\% \text{ Eff} = \frac{P_{OUT}}{P_{IN}} \times 100$$

$$= \frac{(\quad)}{(\quad)} \times 100$$

TRANSFORMER EFFICIENCY	Eff = _____ %

5.7 SECONDARY CENTER-TAP

18. The secondary winding of the transformer used on the CES 306 module has a CENTER-TAP connection. To check the transformer center tap, use the same wiring on the panel (Figure 7) with Switch SA UP to connect R_L across the secondary.

Use the ac voltmeter to measure the three voltages shown below in Figure 8.

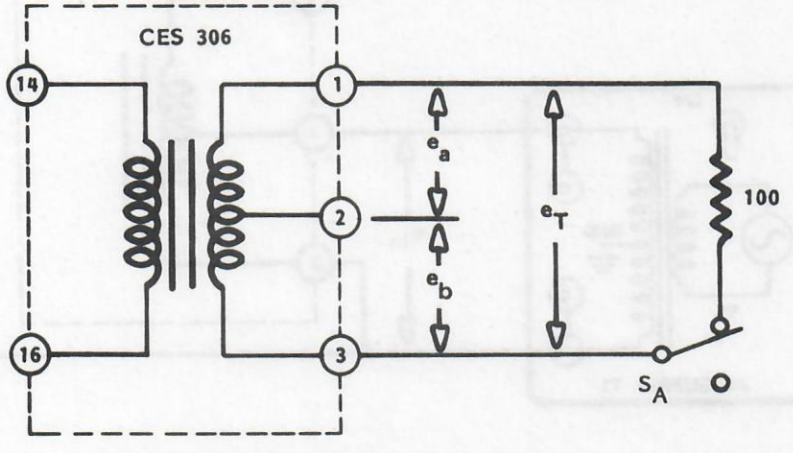


Figure 8 - Center tap secondary measurements; EXPERIMENT.

Enter the voltage readings below.

e_T =	V
e_a =	V
e_b =	V

Observe that e_a is approximately equal to e_b and the sum of e_a and e_b equals e_T indicating that the winding is center-tapped.

5.8 AUTOTRANSFORMERS

19. A transformer can also be implemented using a single winding with a tap. This is called an AUTOTRANSFORMER and is shown in Figure 9.

Wire the circuit shown in Figure 9.

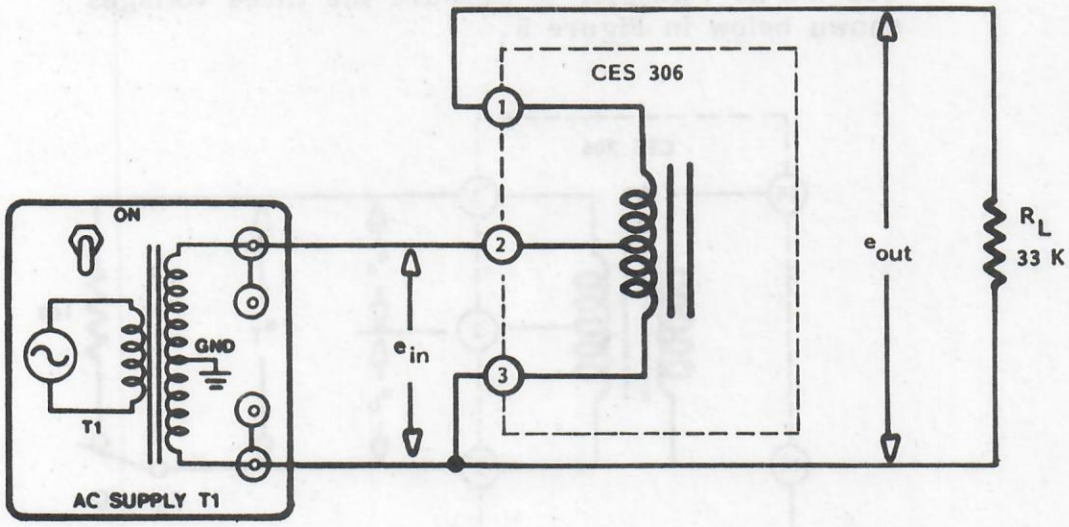


Figure 9 - Autotransformer EXPERIMENT.

20. Measure the ac input and output voltages and record them below.

e_{in} =	V
e_{out} =	V

21. Because the winding in Figure 9 is center-tapped, the turns ratio is 2:1 step up.

    Calculate the ratio of output to input voltages based on the voltages from step 20.

$$TR = \frac{e_{OUT}}{e_{IN}} = \frac{(\quad)}{(\quad)}$$

AUTOTRANSFORMER TURNS-RATIO	TR = _____ : 1 STEP _____ (UP/DOWN)

    The auto transformer consists of only one winding but yet there is a voltage increase.

CONCLUSIONS

We have learned from this experiment that:

The turns ratio of a transformer can be determined from the primary and secondary voltages using the equation:

$$TR = \frac{E_p}{E_s} \text{ or } \frac{E_s}{E_p}$$

Transformer specifications are given in terms of voltages rather than turns ratios.

When a transformer secondary winding is loaded, the primary current flow increases.

Real life transformers suffer losses due to I^2R, eddy currents, hysteresis, and flux leakage.

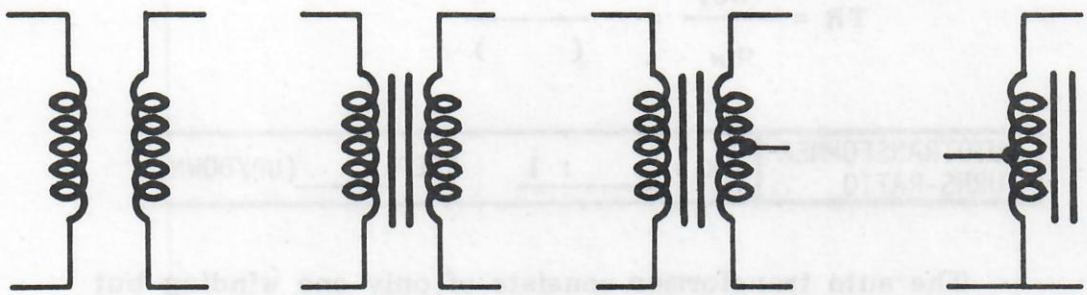
The efficiency of a transformer can be determined from

$$\% \text{ Eff} = \frac{P_{OUT}}{P_{IN}} \times 100$$

Transformer windings are often tapped.

Most tapped windings are center-tapped.

The symbols for transformers are typically:



AIR CORE IRON CORE CENTER TAP AUTOTRANSFORMER

The schematic letter designation for a transformer is T. When more than one transformer is used they are identified as T1, T2, T3, etc.

The autotransformer does not provide electrical isolation between primary and secondary.

ASSIGNMENT

Answer the following True-False questions.

1. A transformer that has a primary voltage of 32 volts and a secondary voltage of 48 volts has a TR of 1.5:1 step-down. _____

2. The current relationship between primary and secondary is given by _____

$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

3. The secondary voltage that can be expected from a transformer is determined from _____

$$E_s = TR \cdot E_p$$

4. Ideal transformers (no losses) are not used frequently because they are too costly. _____

5. In a center tapped winding the voltages across each half of the winding will be approximately equal. _____

6. Taps on transformer windings are always at the electrical center. _____

7. While autotransformers operate with a single winding, they sacrifice the electrical isolation between primary and secondary windings. _____

8. A transformer with an efficiency of 80% and a primary power dissipation of 20 watts can deliver 16 watts to the load. _____

9. Given that one half of a center-tapped winding delivers 20 volts, the full winding must deliver 40 volts. _____

10. An autotransformer has 120 volts applied to a 720 turn primary and the secondary delivers 30 volts. This is a step down action with a 180 turn secondary. _____

KEY TERMS

1. AUTOTRANSFORMER

   A transformer with a single winding in which part of the winding acts as the primary and part as the secondary.

2. CENTER TAP

   A connection made at the exact electrical center of a transformer winding.

3. CORE

   A magnetic material on which a transformer is wound.

4. EDDY CURRENTS

   Currents induced in the transformer core by the magnetic field developed by the primary winding.

5. HYSTERESIS

   The lag in the magnetization of the transformer core material because of molecular friction generated by the magnetic dipoles.

6. I^2R LOSSES

   Heat losses due to the resistance of the wire used to form the transformer windings.

7. IDEAL TRANSFORMER

   A theoretical transformer with no losses.

8. PRIMARY WINDING

   The transformer winding through which the source current flows to create the magnetic field that induces a voltage in the secondary windings.

9. SECONDARY WINDING

   The transformer windings from which output power is taken.

10. STEP-DOWN TRANSFORMER

    A transformer whose secondary output voltage is lower than the primary input voltage.

11. STEP-UP TRANSFORMER

A transformer whose secondary output voltage is higher than the primary input voltage.

12. TAP

A permanent electrical connection on a transformer winding somewhere between the two ends of that winding.

13. TRANSFORMER

A device that consists of two or more windings on a common iron core which can transfer electrical energy from one winding to another by magnetic coupling.

14. TURNS RATIO

The ratio of the number of turns on the primary winding to the number of turns on the secondary winding.

Diode Action 6

OBJECTIVES

When you finish this experiment, you will be able to:

1. Identify the cathode and anode leads of various types of diodes.
2. Forward bias a diode.
3. Reverse bias a diode.
4. Make an ac reading meter using a diode.
5. Measure average, rms and peak ac voltages with a dc meter using a diode and capacitor.

DESCRIPTION

The components described and tested for ac circuits include those shown in Figure 1 below.

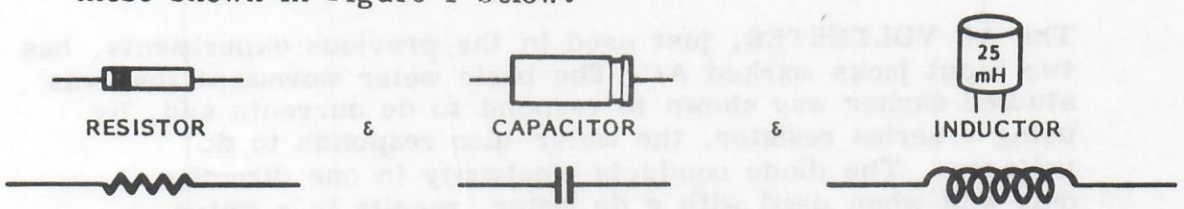
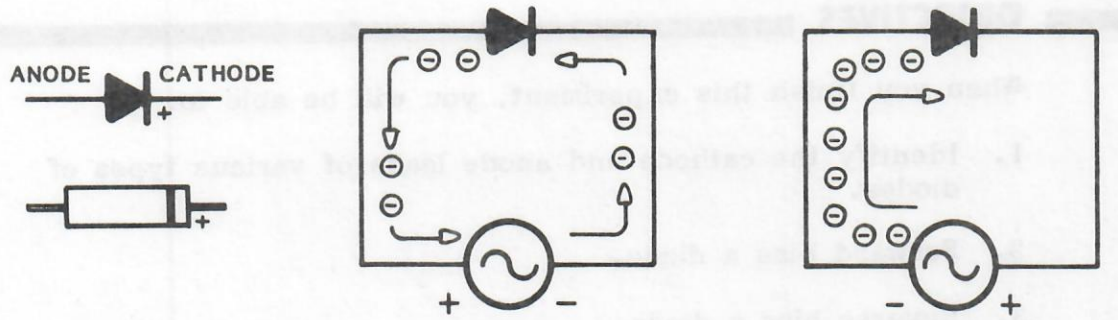


Figure 1 - Two terminal devices used for ac and dc circuits.

These are all two-terminal devices. Another component, the DIODE, discussed briefly earlier when ac was introduced, is a semiconductor device that is generally studied after dc and ac circuits have been covered. Since the diode is also a two-terminal device and has many useful applications in both dc and ac systems, it is introduced now at an elementary level. For example, the ac meter was used in previous experiments but we did not explain how a dc meter movement can be used to measure ac. The ac meter uses a diode with the standard dc meter to measure ac and this circuit is explained and tested in this experiment.

The symbol and appearance of the diode are shown in Figure 2(a). The diode is useful because it allows current to flow through it in one direction only. When the diode is connected to an ac voltage source as in Figure 2(b), electrons will flow through the diode when instantaneous polarity is as shown. The diode is said to be FORWARD BIASED.



(a) DIODE SYMBOL AND APPEARANCE

(b) FORWARD BIASED BY THE INSTANTANEOUS VOLTAGE POLARITY

(c) REVERSE BIASED BY THE INSTANTANEOUS VOLTAGE POLARITY

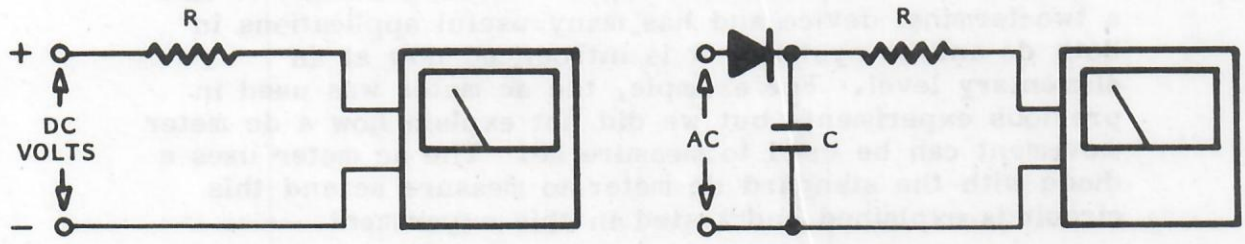
Figure 2 - Diode symbol and electron conduction.

When the polarity of the voltage applied to the diode is reversed, as shown in Figure 2(c), the electron flow is blocked and the diode is REVERSE BIASED.

AC VOLTMETER

The AC VOLTMETER, just used in the previous experiments, has two input jacks marked AC. The basic meter movement that was studied earlier was shown to respond to dc currents and, by using a series resistor, the meter also responds to dc voltages. The diode conducts electricity in one direction only and when used with a dc meter, results in a meter circuit that measures ac.

The simplified diode circuit used to produce an ac voltmeter from a dc meter movement is shown in Figure 3 (b) and is tested in this experiment. A description of the ac voltages of interest follows.



(a) DC VOLTMETER

(b) AC VOLTMETER

Figure 3 - Using a diode to produce an ac voltmeter.

PEAK, AVERAGE AND RMS VOLTAGES

The peak, average and rms voltages were discussed earlier in Experiment 2, G1, Figure 1. The dc meter can be used to measure the peak, average and rms of ac voltages when used with a diode. Consider the circuit shown below in Figure 4.

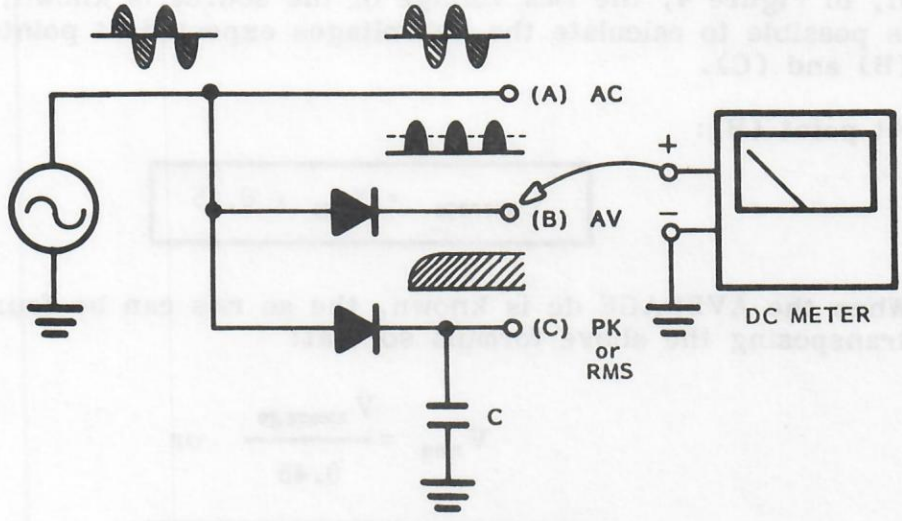


Figure 4 - Ac voltage measurement circuit.

The input to the circuit is ac from the source. Output (A) is ac directly from the source and, if the dc meter lead is connected here, it will read zero volts as explained in earlier experiments.

AVERAGE VOLTAGE

The output voltage at point (B) is half of the full sine wave ac source. The other half of the sine wave has been blocked by the diode when it is reverse biased. When a dc meter is connected to point (B) in Figure 4, the meter will read the AVERAGE dc voltage of the half sine wave output.

PEAK VOLTAGE

The output voltage at point (C) is equal to the PEAK voltage of the ac voltage source. The capacitor, C, charges to the peak voltage and remains charged to this voltage because it cannot discharge through the diode.

RMS VOLTAGE

The output voltage at point (C) is the peak voltage. The rms voltage is equal to the peak voltage times 0.707 and by adjusting the multiplier resistance in the dc meter circuit, the meter scale can be read in rms volts.

If, in Figure 4, the rms voltage of the source is known, it is possible to calculate the dc voltages expected at points (B) and (C).

At point (B):

$$V_{average} = V_{rms} \times 0.45$$

When the AVERAGE dc is known, the ac rms can be found by transposing the above formula so that:

$$V_{rms} = \frac{V_{average}}{0.45} \quad \text{or}$$

$$V_{rms} = V_{average} \times 2.22$$

The expected dc PEAK voltage at point (C) in Figure 7 can be determined, when the rms output is known, from:

$$V_{peak} = V_{rms} \times 1.414$$

When the dc PEAK voltage is known, the rms voltage can be determined from

$$V_{rms} = \frac{V_{peak}}{1.414}$$

or

$$V_{rms} = V_{peak} \times 0.707$$

DIODE LEAD IDENTIFICATION

If you should wire a diode into a circuit with its polarity reversed, it is possible to cause a great deal of damage (but not on the Ed-Lab trainer). There are a variety of diode packaging styles and not all have the polarity clearly marked. Some typical diode packages are shown in Figure 5.

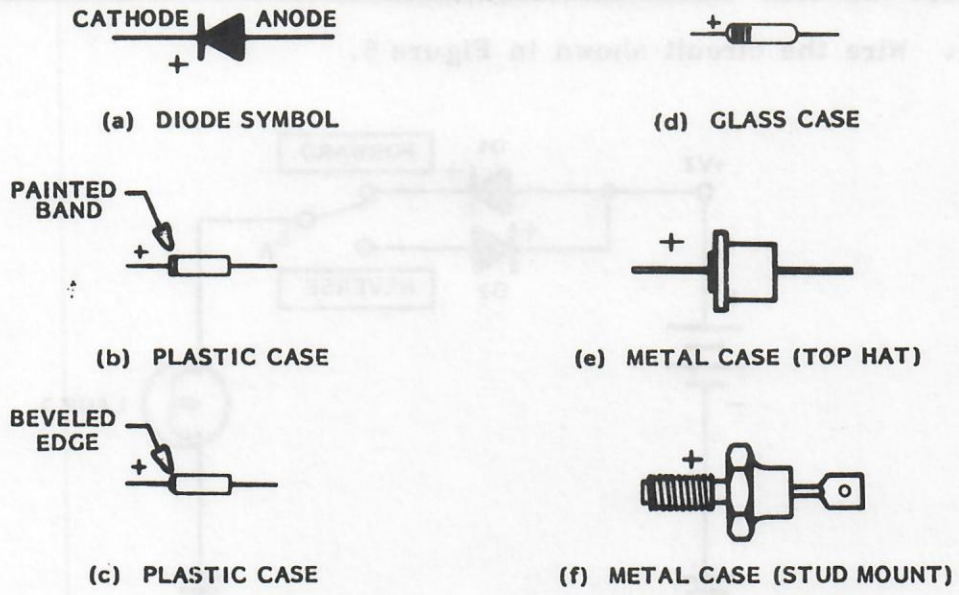


Figure 5 - Diode packages and polarities.

Diode types (b) and (c) in Figure 5 are used for silicon high current types (750 mA to 2 A or more). The glass case (type d) is frequently used for small "signal" diodes of the germanium type. Diode cases (e) and (f) are also used for high current types. The top hat diode current rating is 750 mA and up. The stud mounted diode (f) can be found with ratings of 10 A or greater.

In the procedure of this experiment, you will examine and test the following:

1. Diode operation, forward and reverse biased
2. Diode ac operation
3. Ac Diode Meter
4. Peak and Average reading meter
5. Rms reading meter

PROCEDURE

1. Wire the circuit shown in Figure 6.

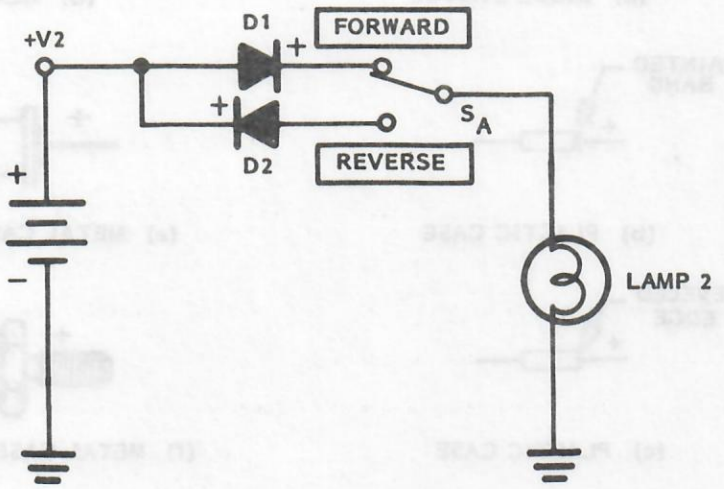


Figure 6 - Diodes in dc circuit; EXPERIMENT.

6.1 DC DIODE OPERATION

2. Place Switch SA UP so that diode D1 is in the circuit.

   Does Lamp 2 light? _____

   Is diode D1 conducting (Forward Biased)? _____

3. Place Switch SA DOWN so that D2 is in the circuit.

   Does Lamp 2 light? _____

   Why? _____

   _____

Enter the results from steps 2 and 3 in Table 1 below and complete the table.

SW A	DIODE	LAMP (ON-OFF)	BIAS (FWD-REV)
UP	D1		
DOWN	D2		

TABLE 1 - Diode states.

The data in Table 1 indicate that a forward biased diode passes electron flow and that a reversed biased diode blocks electron flow.

Does the diode conduct when the ANODE is made positive or negative?

6.2 AC CIRCUIT DIODE OPERATION

4. Remove all wiring and assemble the circuit of Figure 11 on the trainer.

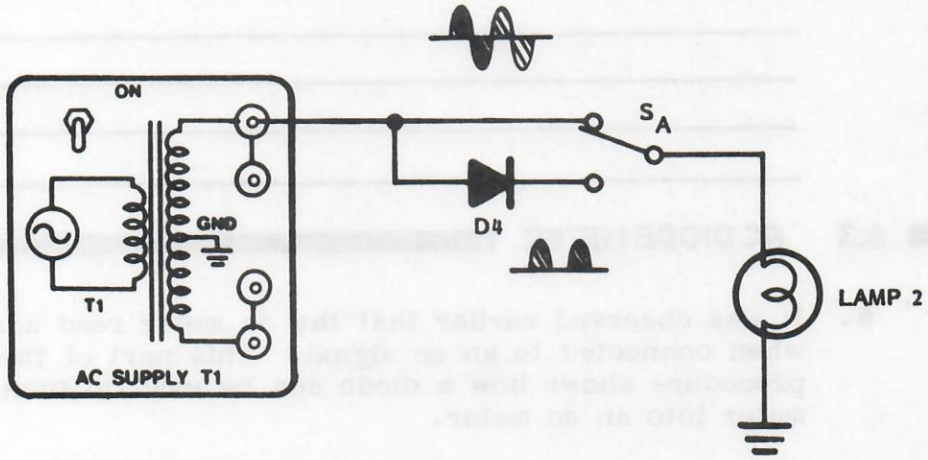


Figure 7 - Diode in an ac circuit; EXPERIMENT.

5. With switch SA UP, the ac is applied directly to the load.

   With switch SA DOWN, the diode is in series with the load.

   Set the switch UP and DOWN and enter the results in Table 4 below.

SWITCH A	LAMP INTENSITY
UP	
DOWN	

TABLE 2 - Lamp intensity.

How do you explain the above results?

What would happen if diode D4 in Figure 7. were reversed?

6.3 AC DIODE METER

6. It was observed earlier that the dc meter read zero volts when connected to an ac signal. This part of the procedure shows how a diode can be used to turn a dc meter into an ac meter.

Wire the circuit shown below in Figure 8.

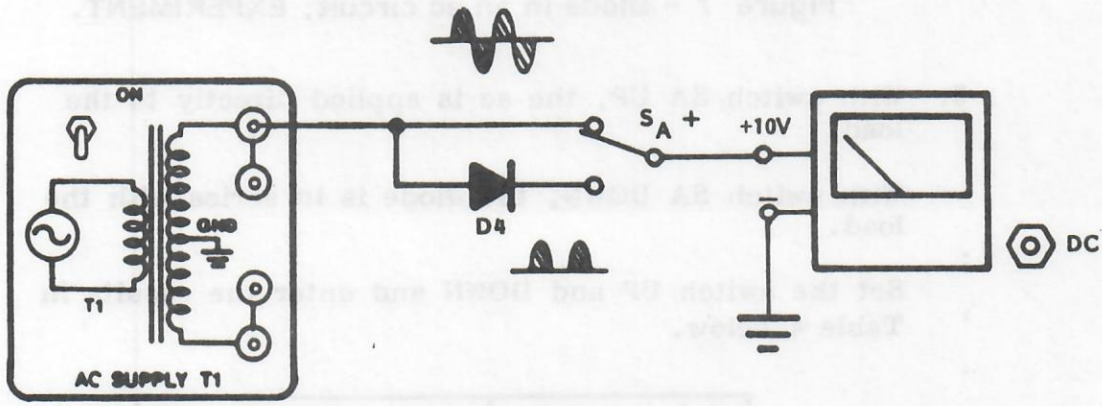


Figure 8 - AC measuring meter using a diode and dc meter; EXPERIMENT.

7. Read the meter with Switch SA UP and DOWN and enter the results in Table 3 below.

SWITCH SA	DIODE	METER READING
UP	NONE	V
DOWN	SERIES	V

TABLE 3 - Dc meter readings with and without diode.

Can a dc meter with a series diode be used to read ac voltages? _____

6.4 PEAK AND AVERAGE READING METER

8. Remove the existing wiring. Set the meter to the 50 volt ac scale and measure the secondary rms voltage as shown in Figure 9.

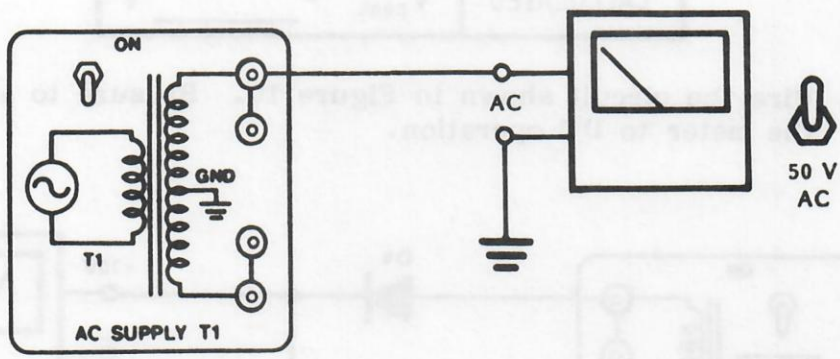


Figure 9 - Ac rms voltage measurment of half the secondary voltage: EXPERIMENT.

Record the rms voltage below.

HALF OF AC POWER TRANSFORMER	V_{ac} = _____ volts rms

9. Calculate the expected average ac voltage for the half wave that corresponds to the rms voltage measured in step 8.

$$V_{average} = V_{rms} \times 0.45$$

$$= (\quad)(0.45)$$

CALCULATED	$V_{average}$ = _____ V

10. Calculate the expected peak ac voltage that corresponds to the rms voltage measured in step 8.

$$V_{peak} = V_{rms} \times 1.414$$

$$= (\qquad)(1.414)$$

CALCULATED	V_{peak} = _____ V

11. Wire the circuit shown in Figure 10. Be sure to set the meter to DC operation.

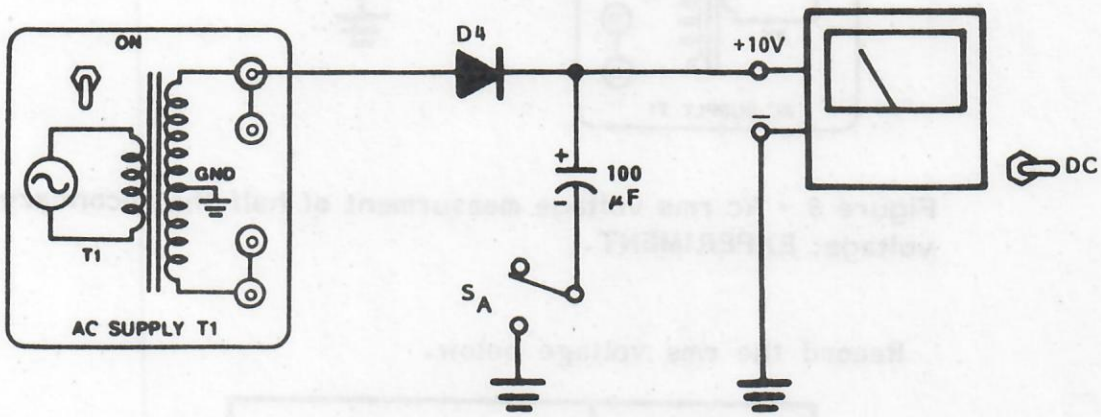


Figure 10 - Ac voltage measurement EXPERIMENT.

12. Set Switch SA to the UP position so that the 100 μF capacitor is out of the circuit.

The output from diode D4 is the average voltage of one half of the ac wave (which is dc).

Measure and record the average voltage.

MEASURED	$V_{average}$ = _____ V

Compare the measured average value above to the average calculated in step 9. How close are they?

_____

_____

13. Set Switch SA DOWN to connect the 100 μF capacitor into the circuit. The meter will read peak as the capacitor holds the charge.

Read and record the peak voltage.

MEASURED	V_{peak} = _____ V

Compare the measured peak value above to the peak calculated in step 10. How close are they?

_____

_____

6.5 RMS READING METER

14. Rewire the circuit as shown in Figure 11 to convert from a peak reading meter to meter that reads rms values.

To do this, shift the lead from the 10 V range to the 50 V range and add the 1 megohm pot in series with the positive meter jack.

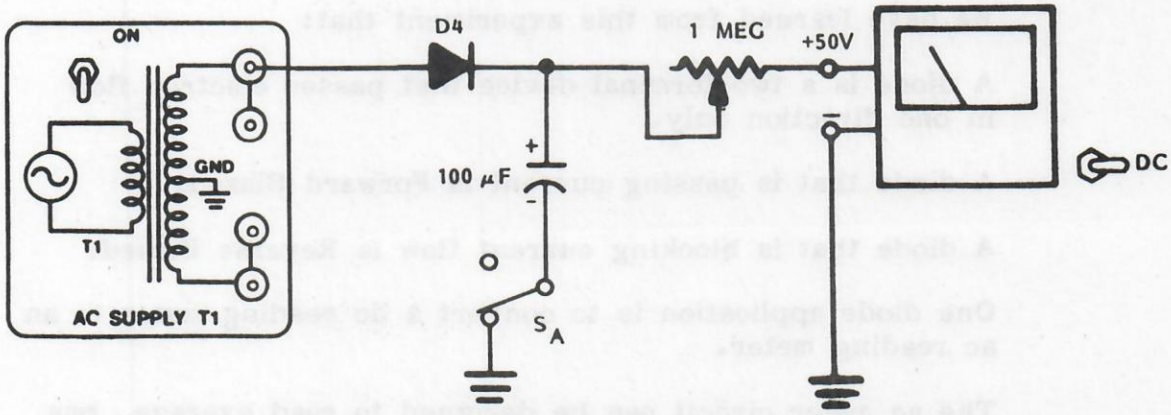


Figure 11 - Rms reading meter EXPERIMENT.

15. Adjust the 1 megohm pot so that the meter reads the actual value of the rms voltage.

The meter is now calibrated to read rms voltage directly. This is the basic concept of how a dc meter reads rms ac voltages using a diode, capacitor and a series resistance.

6.6 VOLTAGE SUMMARY

16. Write in all the measured voltages indicated in Figure 12 below and calculate the peak-to-peak voltage from the available data, given that

$$Vp\text{-}p = 2 \times Vp$$

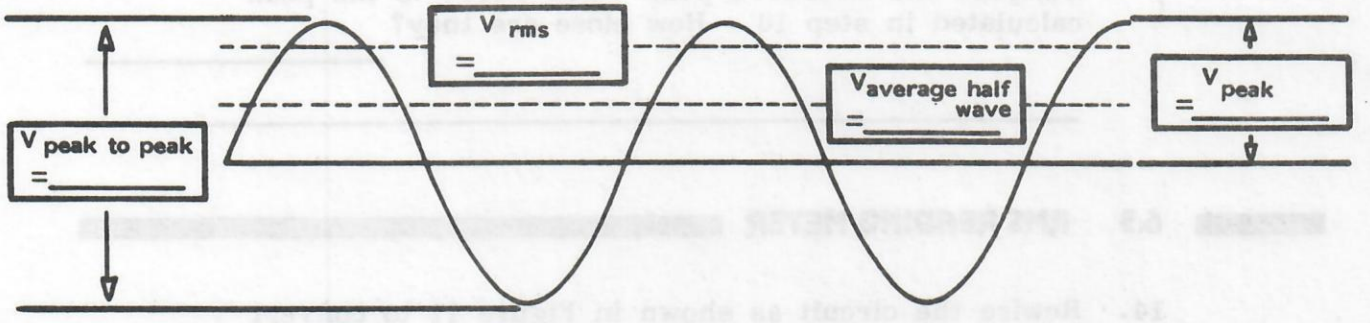


Figure 12 - Results of meter measurements; EXPERIMENT.

CONCLUSIONS

We have learned from this experiment that:

A diode is a two terminal device that passes electron flow in one direction only.

A diode that is passing current is Forward Biased.

A diode that is blocking current flow is Reverse Biased.

One diode application is to convert a dc reading meter to an ac reading meter.

The ac meter circuit can be designed to read average, rms and peak ac voltages.

Diodes are manufactured in different packages each of which are marked to indicate the diode polarity.

ASSIGNMENT

Answer the following multiple choice questions.

1. A diode may be defined as a device that:

   a. has two terminals.
   b. passes current when forward biased.
   c. blocks current when reverse biased.
   d. all of the above.

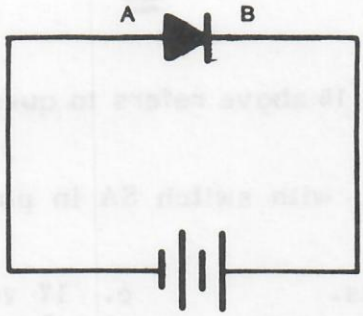


Figure 13 above refers to questions 2 to 4.

2. For the diode shown in Figure 13, terminal:

   a. A is the anode and B is the cathode (+).
   b. B is the anode and A is the cathode (+).
   c. A is the cathode and B is the anode marked (+).
   d. none of the above.

3. The diode shown in Figure 13 is _____ biased and electrons _____.

   a. Reverse; flow from A to B.
   b. Forward; flow from B to A.
   c. Reverse; do not flow.
   d. Forward: flow from A to B.

4. If the polarity of the battery in Figure 13 is reversed, the diode will:

   a. not conduct.
   b. conduct from B to A.
   c. conduct from A to B.
   d. none of the above.

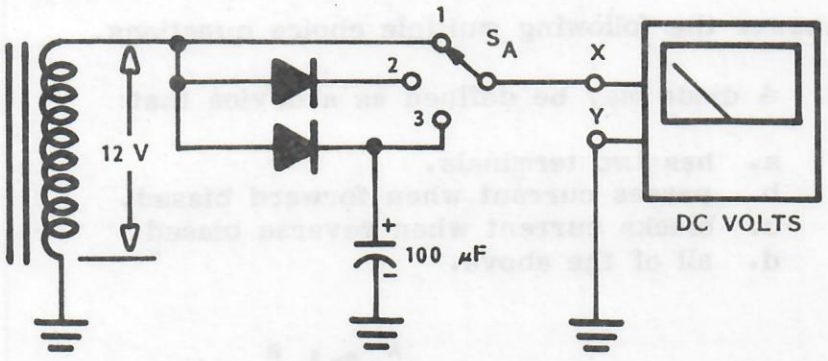


Figure 14 above refers to questions 5 to 9.

5. In Figure 14, with switch SA in position 1, the meter will read:

   a. zero volts.
   b. 12 volts ac rms.
   c. 17 volts peak ac.
   d. 6 volts dc, average.

6. In Figure 14, with switch SA in position 2, the meter will read:

   a. zero volts.
   d. 12 volts ac rms.
   c. 17 volts peak, dc.
   d. 5.4 volts dc, average.

7. In Figure 14, with switch SA in position 3, the meter will read:

   a. 12 volts rms.
   b. 17 volts peak dc.
   c. 5.4 volts average.
   d. 34 volts peak to peak.

8. If a potentiometer is placed in series with lead X to the meter in Figure 14, it can be adjusted so that the meter reads:

   a. directly in rms values in position 3 of SA.
   b. peak voltage in position 1 of SA.
   c. average voltage in position 1 of SA.
   d. any of the above.

9. To read the voltage at point 3 the meter in Figure 14 should have a range, at terminals X Y, of:

   a. 0 to 5 volts dc.
   b. 0 to 15 volts dc.
   c. 0 to 20 volts dc.
   d. any of the above.

10. Given an ac voltage of 20 volts, it is equal to:

    a. 20 volts dc in its heating capability.
    b. 56.56 volts peak-to-peak.
    c. 28.28 volts peak.
    d. all of the above.

KEY TERMS

1. ANODE

   The element to which the stream of electrons flow.

2. CATHODE

   The element from which the stream of electrons flow.

3. DIODE

   A semiconductor device that permits electron flow in one direction only.

4. FORWARD BIAS

   A voltage applied to a semiconductor diode that causes current to flow through the diode.

5. REVERSE BIAS

   A voltage applied to a semiconductor diode that prevents current from flowing through the diode.

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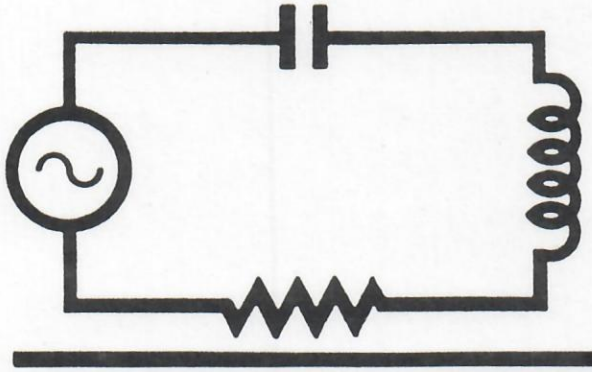
G3-OSCILLOSCOPE OPERATION and APPLICATIONS



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PART G3 - OSCILLOSCOPE OPERATION and APPLICATIONS

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Name _____

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STUDENT PROGRESS & RECORD GUIDE FOR AC PART G3

EXP./INFO.	TITLE	ASSIGNMENT		GRADE
		DATE DUE	DATE SUBMITTED	
Info. Sheet 1	Oscilloscope Operation			
Experiment 1	Waveform Observations			
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Experiment 6	External Test Equipment			
Experiment 7	Construction Project			

Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part G1. Review this lesson.

Ed-Lab
TEXT-LAB MANUAL
OSCILLOSCOPE OPERATION and APPLICATIONS
PART G3

Oscilloscope Operation

INFO SHEET 1

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Draw the basic structure of an electrostatic deflection cathode ray tube (crt).
2. Explain how the electron beam is deflected using electrostatic plates.
3. Describe the function of the horizontal time base circuit.
4. Explain how the waveform of the vertical input is displayed on the crt screen.
5. Define the need for a synchronizing signal.
6. Draw a block diagram of the horizontal sweep system of a basic scope and label the controls.
7. Draw a block diagram of the vertical sweep system and label the controls.
8. Explain the operation of a dual trace oscilloscope.

DISCUSSION

The Cathode Ray Oscilloscope (also called a CRO and a 'scope) presents an accurate plot or graph of voltage versus time on a screen similar to that of a TV set. The screen on which the voltage waveform is displayed is the face of the Cathode Ray Tube or crt. The screen size of the average crt is 5 inches. A typical oscilloscope display of a sine wave is shown below in Figure 1.

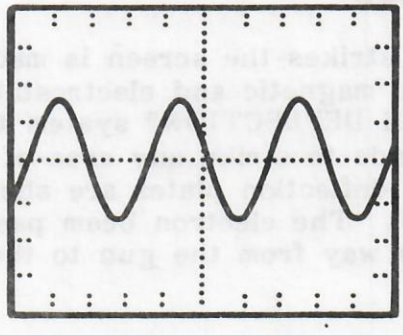


Figure 1 - A typical oscilloscope display of a sine wave.

CATHODE RAY TUBE

The heart of the scope is the cathode ray tube (crt) shown in Figure 2. The crt is made of glass, it is evacuated (vacuum sealed) and contains an electron gun at the base of the tube. The electron gun, made up of a series of cylindrical elements, generates a stream of electrons and forms the stream into a tight sharp beam.

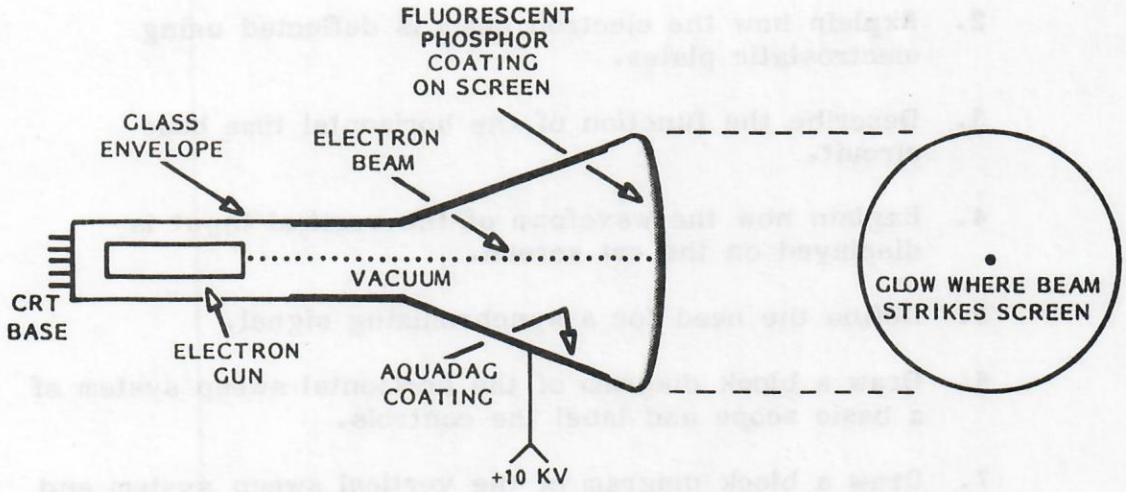


Figure 2 - Simplified description of the construction of a cathode ray tube (crt).

The electron beam formed by the gun is accelerated by the high positive voltage (5 to 12 kv) applied to the Aquadag, a conductive coating on the inside of the flaired portion of the crt as marked in Figure 2. The beam strikes the phosphor coated screen and causes it to glow. The intensity of the glow is determined by the speed and number of electrons in the beam.

BEAM DEFLECTION

The beam that strikes the screen is made up of electrons that respond to magnetic and electrostatic forces. Thus, by adding a "BEAM DEFLECTION" system to the crt, the electron beam can be made to strike any area of the screen. Two sets of electrostatic deflection plates are shown added to the crt in Figure 3. The electron beam passes between each pair of plates on its way from the gun to the screen.

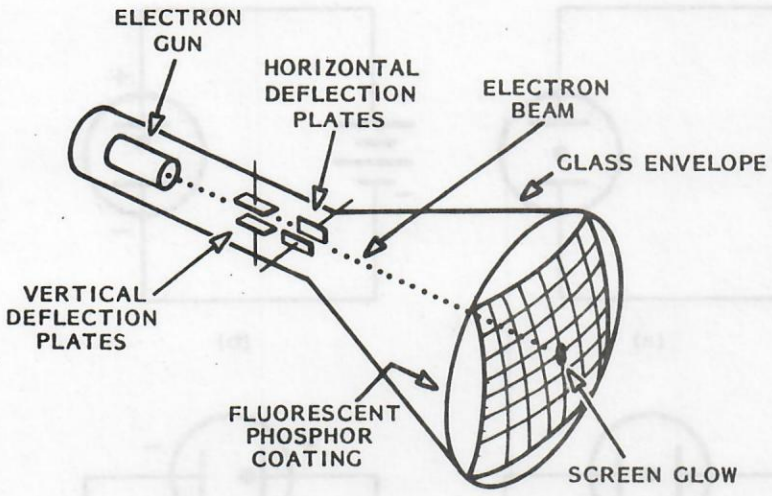


Figure 3 - Cathode ray tube with electrostatic deflection plates, one pair for vertical and a second pair for horizontal deflection.

When a voltage is connected across a set of plates, an electrostatic field is created between the plates. When the electron beam passes between plates it is subjected to the field force which causes the beam to move. This is shown in greater detail in Figure 4(a) to (k). In Figure 4(a), with no voltage applied to the plates, the beam passes through the center unaffected. With voltage applied as in (b), the beam is drawn upward, the negatively charged electrons being attracted to the positive plate. Reversing the polarity, in (c), forces the beam downward.

Applying a voltage to the horizontal plates will move the beam left or right as shown in Figures 4 (d) to (f). Applying voltages to both pairs of plates, simultaneously, moves the beam diagonally, as shown, from (g) to (k). Applying equal values of voltage to both sets of plates will move the beam at a 45 degree angle from the center position to either of the four corners of the screen. The direction of movement, as shown, depends upon the plate polarities. The distance the beam moves in any direction depends solely on upon the strength of the voltage; the greater the voltage the greater the deflection.

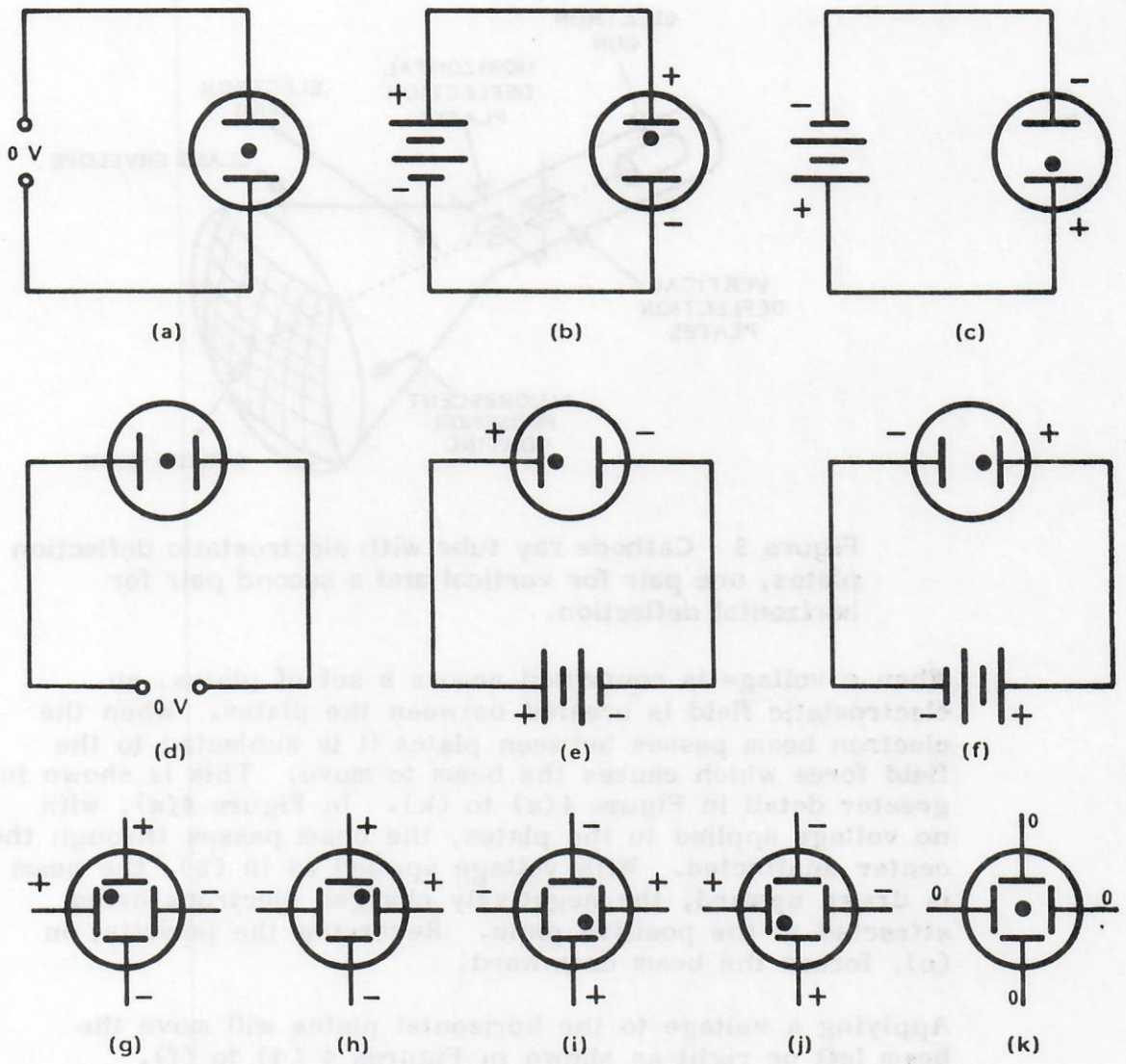


Figure 4(a) to (c) - Deflection with voltage applied to the vertical axis only. (d) to (f) - Deflection with voltage applied to the horizontal axis only. (g) to (k) - Deflection with voltage applied to both axis simultaneously.

AC SWEEP VOLTAGES

The result of the application of an ac voltage (a sine wave) to the vertical plates is shown in Figure 5. As shown in 5(b), the positive alternation will draw the beam from its rest position, upward, and then return to the rest position as the sine wave moves toward its negative alternation. The negative alternation will move the beam downward and back to the rest position.

(a) AC APPLIED TO THE DEFLECTION PLATES.

(b) BEAM MOVEMENT CAUSED BY THE APPLICATION OF AC TO DEFLECTION PLATES.

Figure 5 - Effect of applying ac to the vertical deflection plates.

If the frequency of the applied ac voltage is very low, 1 or 2 Hertz, the screen appearance will be the obvious movement of the beam or the dot. If, however, the frequency of the applied ac is increased to 30 Hz or more the screen display will be a solid, bright, vertical line. The very same effect will occur if the ac voltage is applied to the horizontal plates. A bright horizontal line will appear on the screen.

HORIZONTAL SWEEP

The horizontal movement of the electron beam in an oscilloscope is created by an ac voltage with a RAMP or SAWTOOTH waveshape. As shown in Figure 6, the ramp voltage provides a linear sweep across the screen. This means that a change of 1 volt, for example, anywhere along the rise of the ramp will produce the same amount of electron beam movement across the screen. The movement of the electron beam across the screen, as shown in Figure 6, is called the HORIZONTAL SWEEP. The voltage rise from A to B moves the beam from left to right, gradually at a linear rate. The voltage change from B to C is very rapid and the beam snaps back to the left starting position so quickly that no trace or glow appears: this is called RETRACE.

The horizontal sweep ramp voltage is generated by special circuits inside the scope. These circuits are called the SWEEP GENERATOR or the TIME BASE GENERATOR.

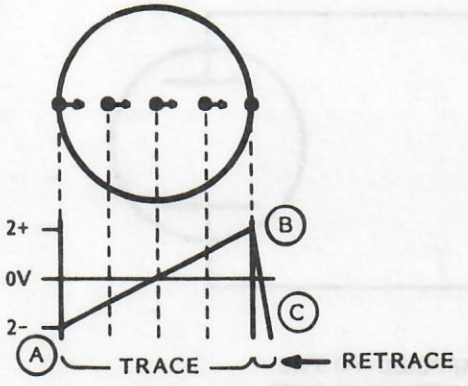


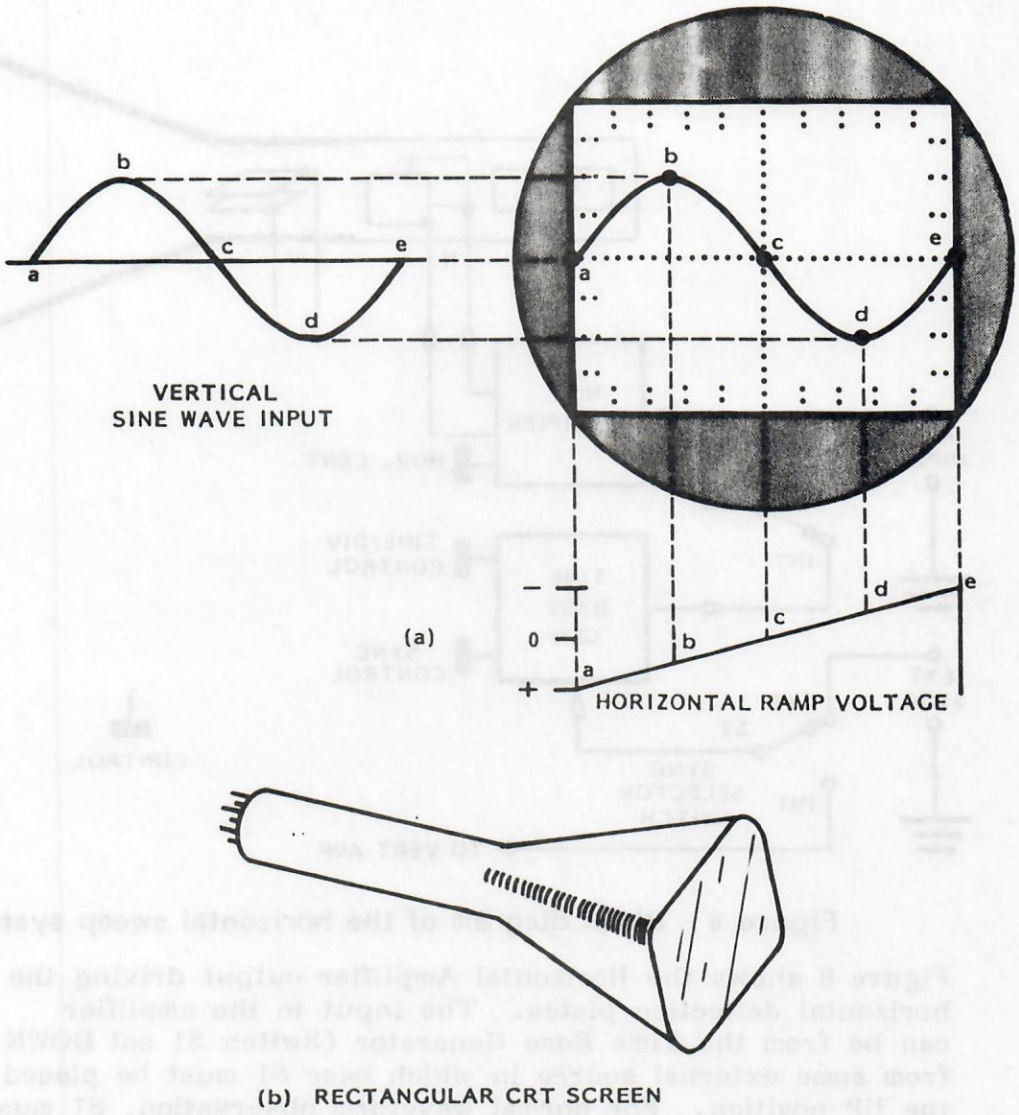
Figure 6 - The horizontal sweep in an oscilloscope is accomplished using a ramp voltage (also called a sawtooth waveform).

WAVEFORM PRESENTATION

One of the major functions of the scope is to display voltage waveforms in a graph format on the crt screen. To help view waveforms in this manner a clear plastic screen, variously called a GRATICULE, GRID, SCREEN or MASK, is placed in front of the crt face as shown in Figure 7(a). As shown, a considerable area of the screen is lost (shaded portion). To reduce the loss and reduce the size of the scope housing, crts with rectangular screens (Figure 7(b)) are now used rather than round types.

In Figure 7(a) when both the horizontal and vertical voltages are starting at points (a), the beam will strike the screen at point (a). As the horizontal and vertical voltages approach point (b), the beam will be moved to point (b) on the screen. Repeating this logic for points (c), (d) and (e), quickly shows how the sine wave input to the vertical plates is graphically presented on the screen.

When both the horizontal and vertical waves are completed (points e), the ramp voltage drops sharply negative causing the beam to retrace to point (a) on the screen. At the same time the vertical sine wave input starts the next cycle, a repeat of the first, and the wave is "drawn" over the first cycle keeping the display bright.



(b) RECTANGULAR CRT SCREEN

Figure 7(a) - Crt screen display for a sine wave applied to the vertical deflection plates and a ramp voltage to the horizontal plates. The graticule allows easy measurement of waveform. (b) - Crt with a rectangular screen.

HORIZONTAL SWEEP SYSTEM

The horizontal ramp voltage is generated by an electronic circuit called the Time Base Generator. The output voltage level of this generator is not great enough to produce movement of the beam across the full width of the crt if applied directly to the deflection plates. As a result it is necessary to strengthen the output of the Time Base Generator using a circuit called an AMPLIFIER. Amplifiers are the subject of later experiments. A block diagram of this arrangement is shown in Figure 8.

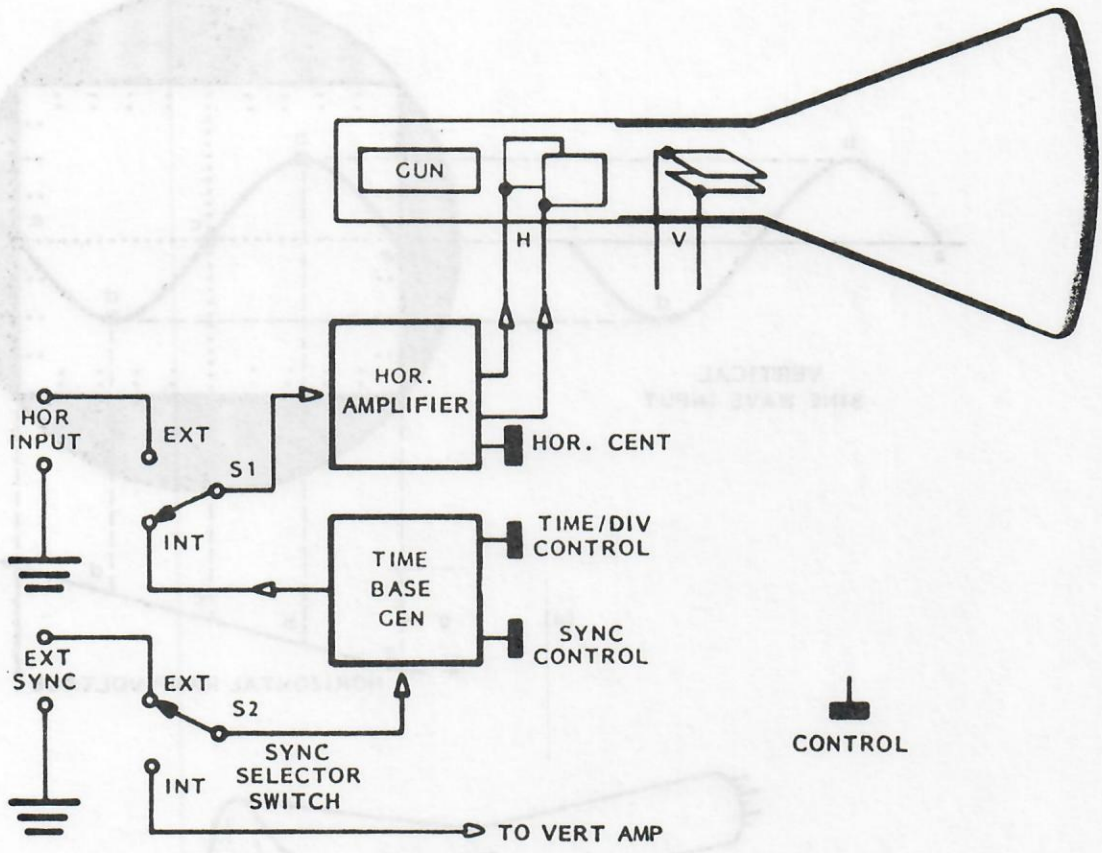


Figure 8 - Block diagram of the horizontal sweep system.

Figure 8 shows the Horizontal Amplifier output driving the horizontal deflection plates. The input to the amplifier can be from the Time Base Generator (Switch S1 set DOWN) or from some external source in which case S1 must be placed in the UP position. For normal waveform observation, S1 must be connected to the Time Base Generator (INTERNAL).

The HORIZONTAL CENTERING control permits the screen display to be moved from side to side. This allows the sine wave position to be adjusted to start precisely from point (a) of the crt screen in Figure 7(a).

The TIME/DIV Control sets the time required for the beam to move one division horizontally. For the typical oscilloscope, the TIME/DIV will range from 0.2 S to 0.2 μS in 18 steps.

SYNCHRONIZATION

As shown earlier in Figure 7, the horizontal ramp voltage and the vertical sine wave have to start and end their trace together. This is called SYNCHRONIZATION. If the two waveforms do not start together, the waveform shown on the screen will be either a jumble of lines or the waveform will drift left or right.

To synchronize the two ac voltages, part of the vertical signal is fed back to the Time Base Generator circuit causing it to lock into the proper frequency relationship with the vertical input voltage.

The SYNC SELECTOR switch, S2, allows selection of a synchronization signal from some source outside of the oscilloscope. The SYNC CONTROL, also called the TRIGGER CONTROL permits adjustment of the sync voltage level to provide a stable screen presentation.

VERTICAL SWEEP CIRCUIT

The vertical deflection plates in the crt of Figure 9 need large voltages to deflect the beam (100 to 200 volts), as do the horizontal deflection plates, thus also requiring an amplifier. The waveform to be observed is now connected to the input of the Vertical Amplifier and the output of the amplifier drives the deflection plates to move the beam vertically.

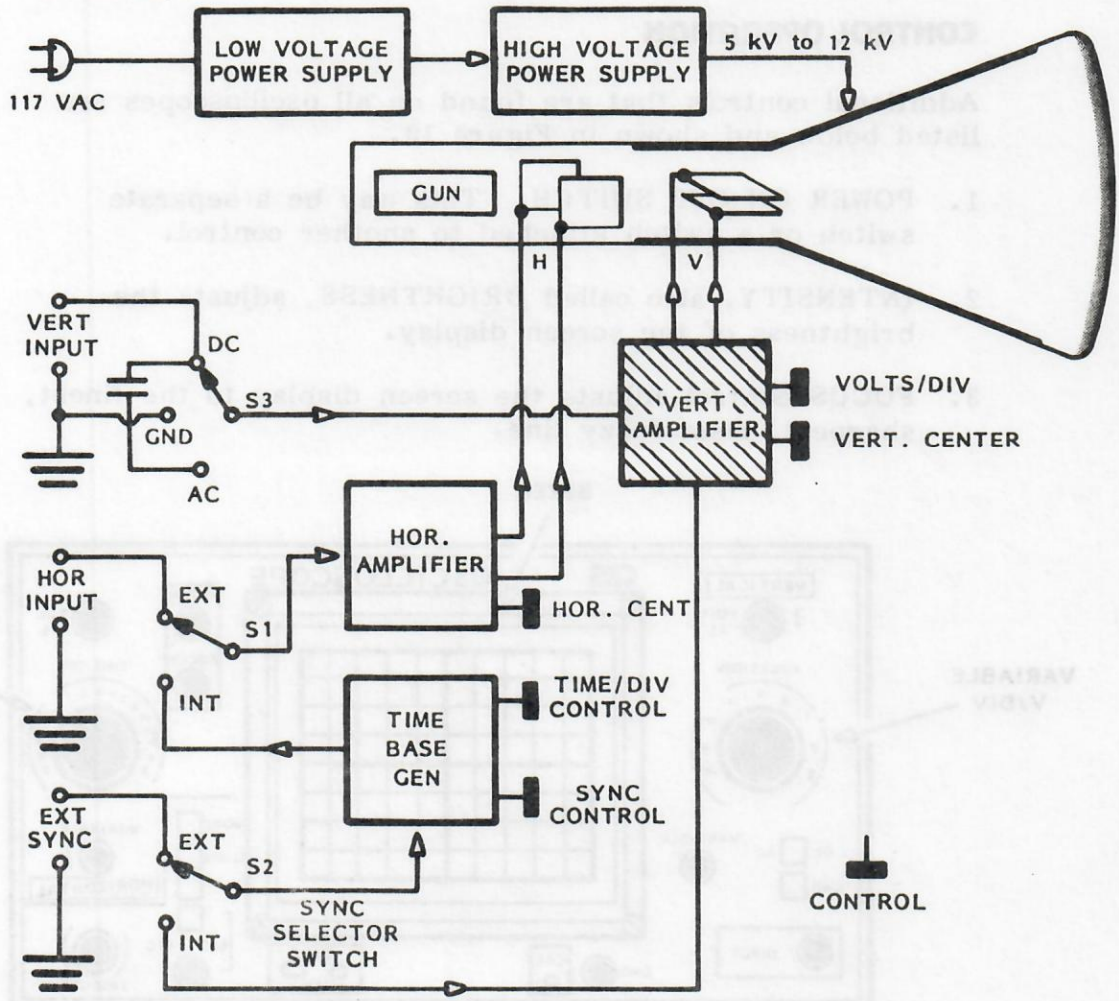


Figure 9 - Complete block diagram of the oscilloscope with the Vertical Amplifier and Power Supplies added.

The controls added to the oscilloscope for the vertical sweep circuit are the VOLTS/DIV switch and the input switch. If the V/DIV switch is set at 2, each division on the graticule (each of which measures 1 cm) has a value of 2 volts. The sine wave displayed in Figure 7(a) covers four divisions and so the peak-to-peak value of the signal displayed is equal to

$$V_{pp} = (\text{No. of Divisions})(\text{V/DIV setting})$$
$$= (4)(2) = \underline{8 \text{ V p-p}}$$

Switch S3 in the vertical input circuit has three positions. The top position is a direct wire feed which will pass dc. The center position grounds the amplifier input; this is helpful when making some adjustments and is explained in the Oscilloscope experiments. The lower position adds a capacitor into the input circuit that prevents the passage of dc but permits ac to pass.

CONTROL OPERATION

Additional controls that are found on all oscilloscopes are listed below and shown in Figure 10.

1. POWER ON-OFF SWITCH. This may be a separate switch or a switch attached to another control.

2. INTENSITY, also called BRIGHTNESS, adjusts the brightness of the screen display.

3. FOCUS control adjusts the screen display to the finest, sharpest, least fuzzy line.

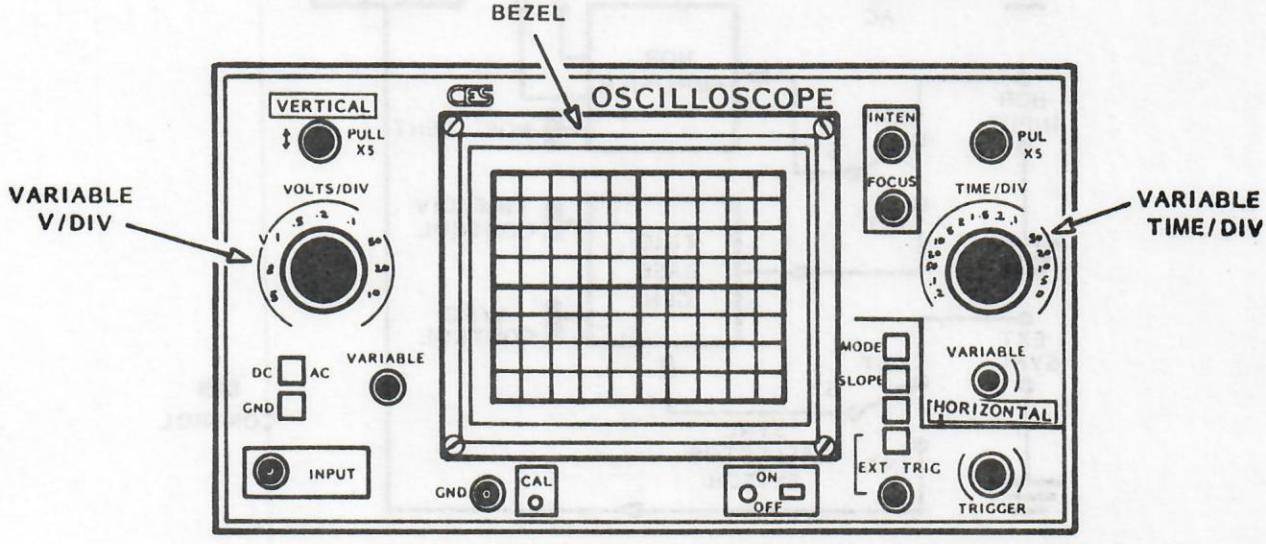
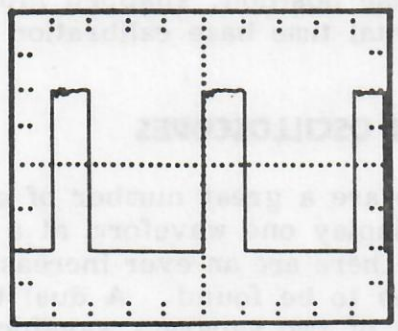


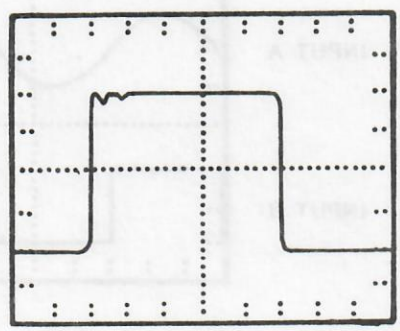
Figure 10 - Typical basic single trace oscilloscope. The bezel is a grooved rim around the crt cut-out that holds the graticule in place.

Controls that may be found on some types of oscilloscopes are:

1. SWEEP MAGNIFIER - When turned on, the Sweep Magnifier control expands the horizontal display by 5 or 10 times, as marked on the panel (5x or 10x). This enables small changes in the waveform to be examined closely but requires that the Brightness control setting be increased. Magnifier control operation is illustrated in Figure 11 below.



(a) NORMAL



(b) MAGNIFIED x5

Figure 11(a) - Normal display of a square wave with an irregularity. (b) - Magnifier expands trace so that the irregularity can be examined more closely. The first and third square waves can no longer be seen on the screen.

2. SYNC AUTO/NORMAL - When the Sync Auto/Normal switch is placed in the Auto position, a horizontal sweep will be generated only when there is a vertical input signal. This is known as TRIGGERED SWEEP. In the Normal position, the horizontal sweep appears continually.

3. VARIABLE GAIN - This control is found in the Vertical Amplifier and allows precise adjustment of the vertical height of the screen display. This is in addition to the vertical gain control of the V/DIV switch.

   To be sure the Calibration of the V/DIV switch is correct, the Variable control must be set fully clockwise until the detent snap is felt.

4. VARIABLE TIME/DIV - This control is located in the Time Base Generator circuit and allows continous adjustment of the Time Base frequency. If not in the extreme clockwise position, snapped into the detent, the horizontal time base calibration will be incorrect.

DUAL TRACE OSCILLOSCOPES

While there are a great number of oscilloscopes in use that can only display one waveform at a time, as shown in Figure 10, there are an ever increasing number of DUAL TRACE oscilloscopes to be found. A dual trace scope permits the observation of two separate waveforms at the same time as shown in Figure 12.

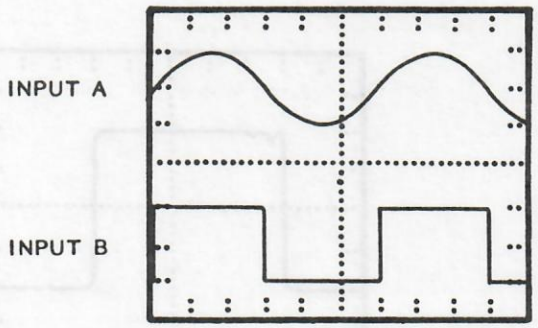


Figure 12 - Typical crt display on a dual trace oscilloscope.

A dual trace scope usually uses the same type of cathode ray tube as the single trace scope but employs circuitry that allows a time sharing arrangement for the beam. Two methods of time sharing are used. These are

CHOP MODE for Low Frequency
ALTERNATE MODE for High Frequency

CHOP MODE

The sharing of the beam in the chop mode is shown in Figure 13. Each sweep, channel A and B, is chopped. Part of the trace appears in each sweep successively. The length of the on-off times are exaggerated as a typical sweep rate is 250 kHz.

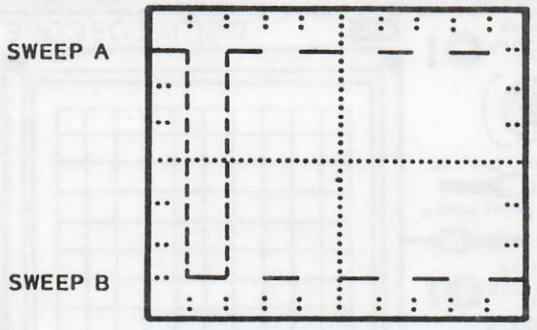


Figure 13 - Chop mode method of sharing the beam. The exchange rate is typically 250 kHz.

The chop mode does not usually affect the waveform presentation because its chop rate is so high. It can, however, cause small gaps to appear in the waveform if the chopping frequency is an even multiple of the waveform frequency being observed. If this happens, it is helpful to switch to the Alternate mode, if possible.

ALTERNATE MODE

In the Alternate mode, the first horizontal sweep produces the channel A input and the next sweep the channel B input. Each successive sweep reproduces one of the channels, in turn. This mode of presentation works well for the observation of high frequency signals but shows flicker at lower frequency displays.

DUAL TRACE CONTROLS

Dual trace oscilloscopes have two Vertical Input Channels labeled A and B or 1 and 2. Each of these vertical channels have the same controls as the single trace vertical. This is shown in Figures 14 and 15. Note that each channel has its own centering control so that either one can be positioned on top or bottom of the display.

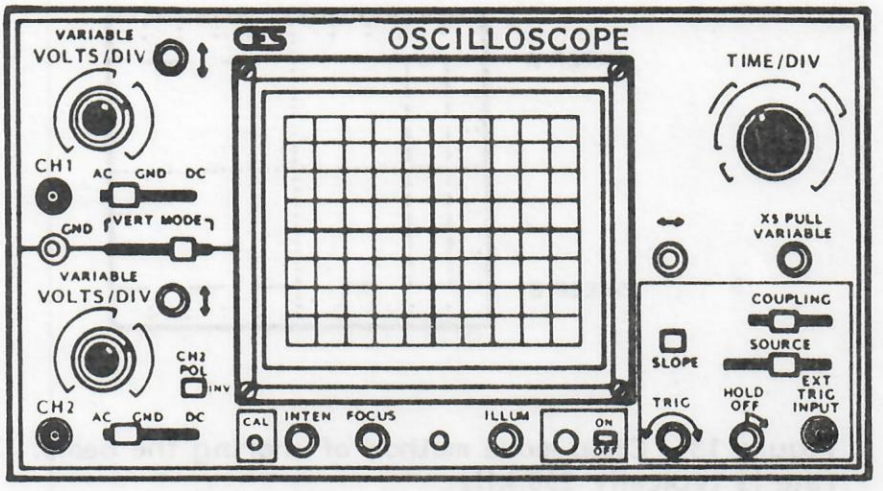


Figure 14 - Dual trace vertical input controls are identical to those provided for single trace scopes. The added control is the VERTICAL MODE switch that allows selection of the vertical display as shown above.

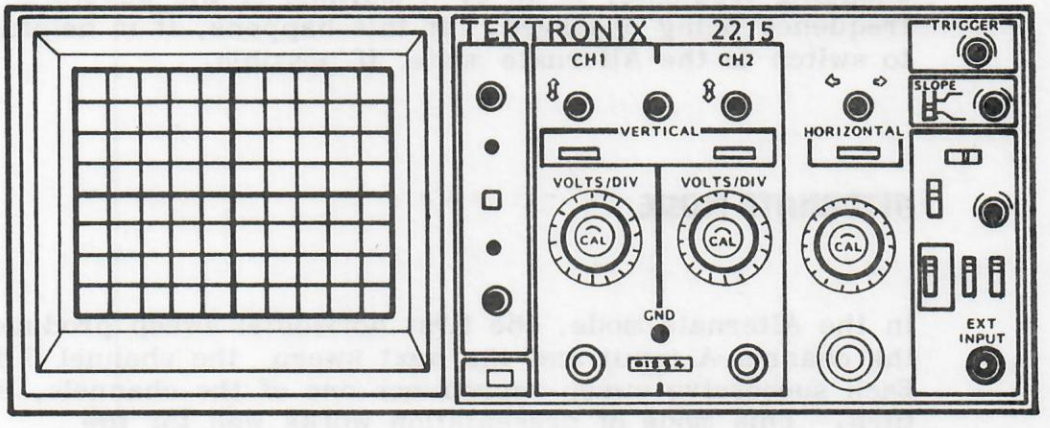


Figure 15 - Tektronix Model 2215 dual trace oscilloscope.

The VERTICAL MODE switch that has been added to the dual trace scope allows for the following selections:

CH 1 - Only the voltage that has been applied to the CH 1 input will appear on the screen.

CH 2 - Only the voltage that has been applied to the CH 2 input will appear on the screen.

ALT - Voltages that have been applied to both CH 1 and CH 2 appear on the screen alternately. This setting is preferred for high frequency inputs.

CHOP - At this setting, the inputs to CH 1 and CH 2 are switched at a rate close to 250 kHz no matter what the time base frequency is. This setting is best for low frequency waveform observation.

ADD - The algebraic sum of the input voltage applied to CH 1 and CH 2 will appear on the screen.

Many dual trace scope mode switches do not have a Chop and Alternate selection. They have only a CH 1 , CH 2 and DUAL. The internal scope switching circuits select the chop or alternate modes according to the horizontal time base frequency setting.

OSCILLOSCOPE APPLICATIONS

Some of the more common appplications for the oscilloscope are listed below.

1. Waveform observation.
2. Dual Trace waveform comparison.
3. Voltage measurement (dc, peak and p-p).
4. Frequency measurement.
5. Time interval measurement.
6. Phase measurement.
7. Rise and fall time measurement.

These applications will be explored in the experiments that follow.

CONCLUSIONS

We have learned from this information sheet that:

The cathode ray oscilloscope presents a visual plot of voltage versus time on the crt screen.

The crt forms an electron beam that is deflected across the screen surface by two pairs of electrostatic deflection plates.

The signal waveform to be observed must be connected to the vertical deflection system.

The horizontal deflection system must be driven by a ramp voltage in order to observe the waveform applied to the vertical deflection system.

In order to see a single cycle of the vertical input signal, the horizontal sweep frequency must equal the frequency of the vertical input signal.

To see more than one cycle of the vertical input signal, the horizontal sweep frequency must be less than the frequency of the vertical input signal.

In order for the screen display to be steady, the horizontal sweep frequency must be equal to or a sub-multiple of the vertical input frequency and synchronized with the vertical signal.

The source of the sync signal is selected by the SYNC SOURCE switch and may be INT, EXT or 60 Hz. For a dual trace scope the sources may be CH 1, CH 2, ALT, EXT or 60 Hz.

The horizontal sweep frequency selector is calibrated in time, not frequency. This is the control marked TIME/DIV. It indicates the time of one horizontal division.

The vertical sweep system is calibrated in VOLTS/DIV and indicates how many volts are required to sweep one division vertically.

The MAGNIFIER controls the horizontal width and expands the display to 5 times its normal width. All time measurements then have to be divided by 5.

When measuring voltage or frequency with an oscilloscope, all variable controls must be placed in the CALIBRATE position.

The dual trace oscilloscope can be used to measure the phase difference between two signals.

ASSIGNMENT

Answer the following True-False questions.

1. The heart of the oscilloscope is the cathode ray tube, crt. ____
2. The crt is a vacuum tube. ____
3. The electron beam is formed by the deflection plates. ____
4. The accelerating high voltage is connected to the Aquadag, a conductive coating inside the flare of the crt. ____
5. When the electrons strike the crt screen the electrons emit light. ____
6. The deflection plates can be used to move or deflect the electron beam using magnetic energy. ____
7. To display a waveform on the crt screen it is necessary to provide a ramp voltage for horizontal sweep. ____
8. By moving and aiming the electron gun in the crt properly, it is possible to strike any part of the fluorescent screen. ____
9. An ac voltage of any waveshape, when applied to the vertical deflection plates, will create a vertical line on the crt screen if there is no horizontal defection. ____
10. The horizontal sweep waveform is a sawtooth, also called a ramp voltage. ____
11. If the horizontal time base generator circuit is not synchronized with the vertical signal, the crt display could drift left or right. ____
12. The horizontal sweep is calibrated in VOLTS/DIV. ____
13. The vertical sweep is calibrated in TIME/DIV. ____
14. The function of the Focus control is to adjust the display on the crt so that it is as sharp and thin as possible. ____
15. The function of the Intensity control is to adjust the brightness of the display. ____

16. The function of the x5 Magnifier control is to expand the display so that instead of one cycle appearing on the screen 5 cycles will appear. ____

17. A dual trace oscilloscope can present two separate displays on one crt screen but requires a crt with two electron guns. ____

18. A dual trace scope with two vertical inputs can display the input of CH 1 or CH 2. ____

19. A dual trace scope can display the CH 1 and 2 inputs simultaneously or the sum of both the 1 and 2 inputs. ____

20. In a dual trace scope the Chop mode is preferable for the observation of low frequency ac voltages. ____

KEY TERMS

1. ALTERNATE SWEEP

   A dual trace mode of operation where the signal from CH B is displayed after the signal from CH A is displayed.

2. CALIBRATE CONTROL POSITION

   The positions of the Variable vertical V/DIV and horizontal TIME/CM controls that provide the amplitude and time values printed on the scope panel.

3. CATHODE RAY TUBE (crt)

   A vacuum tube in which the electron beam is focused on a fluorescent screen. The beam can be moved, focused and varied in intensity.

4. CENTERING CONTROLS

   Controls that allow the screen presentation to be moved horizontally (HOR CENT) or vertically (VERT CENT).

5. CHOP

   A dual trace mode of operation in which the display is switched back and forth between the two channels at a fixed rate.

6. DEFLECTION

   The movement of the electron beam in a crt, most often accomplished electrostatically, causing the beam to traverse the crt screen.

7. DETENT

   A stop position on a control or switch used to lock into a rotary position setting such as for the calibrate position of some rotary controls.

8. DISPLAY

   The visual presentation of a waveform on a crt.

9. DUAL TRACE OSCILLOSCOPE

   A scope that has two separate vertical circuits and can display them both at once.

10. ELECTRON BEAM

A narrow stream of electrons formed by the electron gun in the crt neck that flows toward the fluorescent screen face. The beam can be controlled by electrostatic or magnetic fields. Often called the Z axis.

11. ELECTROSTATIC DEFLECTION

Movement of the electron beam by passing the beam between two metal plates that have a voltage across them. The beam will move toward the positive plate and away from the negative plate.

12. FOCUS

The scope control that determines the sharpness of the screen display.

13. GRATICULE

The grid lines on the plastic in front of the crt screen, marked off in cm squares. Used for measurements of the displayed signal. Also called Grid.

14. HORIZONTAL DEFLECTION

The movement of the electron beam in the horizontal direction on the crt face. Often referred to as the X axis.

15. OSCILLOSCOPE

An instrument that displays instantaneous values of voltage, against time, on a crt screen. Also called a scope.

16. SCREEN

The surface of the crt that is coated with a chemical that fluoresces when struck by the electron beam.

17. SPOT

The area on a crt face that glows when the electron beam strikes the screen. The spot is clearly visible when there is no deflection.

18. SWEEP

The continuous movement of the beam in the horizontal (Hor. Sweep) or vertical (Vert. Sweep) directions.

19. SYNCHRONIZATION

The precise matching of the horizontal sweep frequency to the vertical signal frequency. The horizontal time base must be equal to the vertical or some multiple of it to keep the display steady.

20. TIME BASE

The ramp voltage generated by the horizontal sweep generator circuit, called the Time Base generator. The time base is controlled by the TIME/DIV switch.

21. TRACE

The display of a voltage waveform on the crt screen.

22. TRIGGER

The signal that causes the horizontal sweep of the scope to start moving across the screen.

23. VERTICAL DEFLECTION

The movement of the electron beam in the vertical direction on the crt face. Often referred to as the Y axis.

24. WAVEFORM

The screen presentation of the variation in voltage (vertical) versus time (horizontal).

25. X AXIS

The horizontal axis of the display.

26. Y AXIS

The vertical axis of the display.

27. Z AXIS

The axis of the electron beam in the crt.

Waveform Observations 1

OBJECTIVES

When you finish this experiment, you will be able to:

1. Locate and identify the major operating controls on a triggered oscilloscope.
2. Set all the controls of the oscilloscope to display sine, triangle and square waves.
3. Observe the effect of a dc voltage input on the screen display.
4. Observe the effect of stray pick-up on the 'scope display.

ADDITIONAL EQUIPMENT

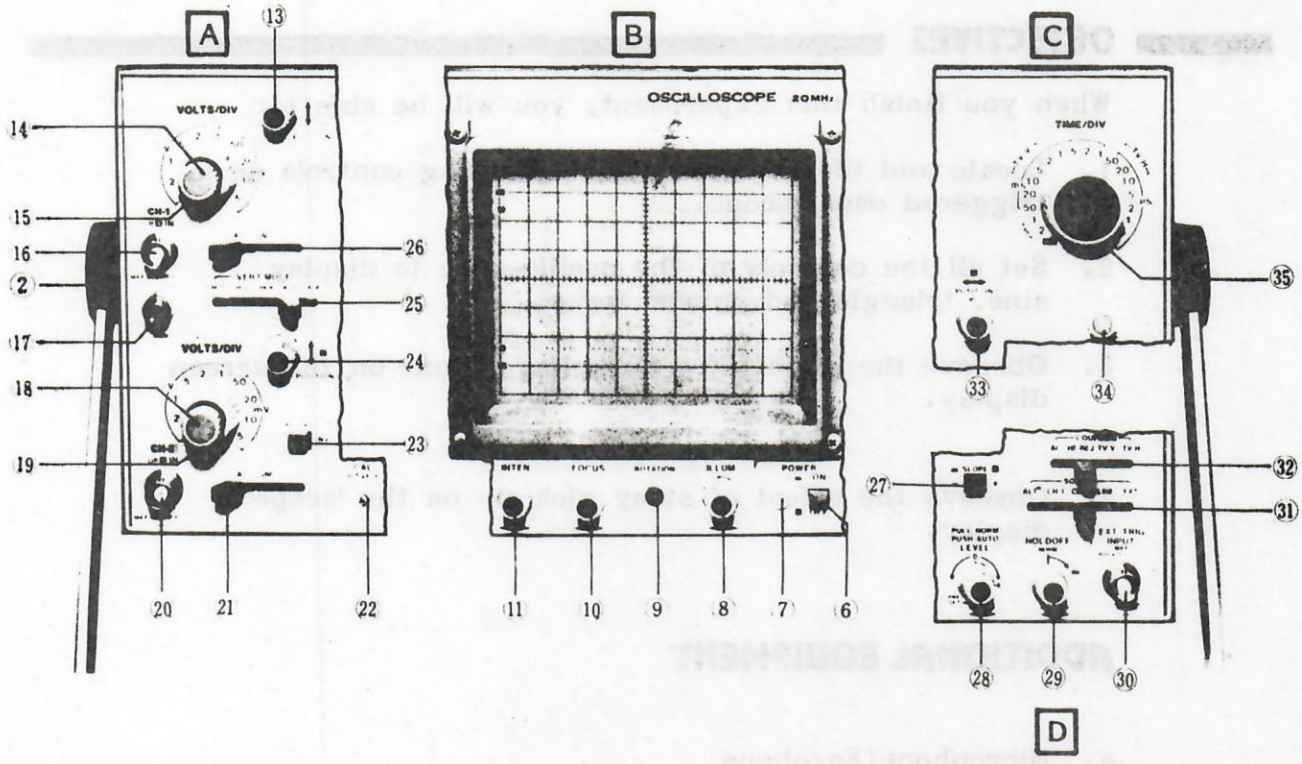
a. Microphone/Earphone
b. 3-Banana to BNC adapters
c. Dual Trace Oscilloscope, CES 4708 or equal.

(All further experiments use the oscilloscope but will not be referenced under the "Additional Equipment" list at the beginning of the experiment.)

DESCRIPTION

In the ac experiments in Part F2, we measured the ac voltages with meters, observed the effects of ac on lamp intensity and listened to ac on the loudspeaker. In this experiment you will use the oscilloscope to provide a visual display of the ac waveform so that the waveshape can be observed and measurement made of amplitude and frequency.

The control layout and control function designations for different model oscilloscopes are generally similar. Some typical oscilloscopes were illustrated earlier in Information Sheet 10. The front panel view of a typical modern dual trace oscilloscope is shown again in Figure 1 for ease of reference. The oscilloscope you are using may be different.



⑥ POWER ▬/▮ON/OFF

⑧ ILLUM

⑨ ROTATION ⊘

⑩ FOCUS

⑪ INTEN

⑬ ↕ (CH-1)

⑭ VARIABLE (CH-1)

PULL x 10

⑮ VOLTS/DIV (CH-1)

⑯ CH-1 IN

⑱ VARIABLE (CH-2)

PULL x 10

⑲ VOLTS/DIV (CH-2)

⑳ CH-2 IN

㉑ AC-GND-DC (CH-2)

㉒ CAL 0.5Vp-p

㉓ CH-2 POL.

㉔ ↕ (CH-2)

㉕ VERT MODE

㉖ AC-GND-DC (CH-1)

㉗ SLOPE

㉘ LEVEL

PULL NORM/PUSH AUTO

㉙ HOLDOFF

㉚ EXT TRIG INPUT

㉛ SOURCE

㉜ COUPLING

㉝ ↔

㉞ TIME VARIABLE

PULL x 10 MAG

㉟ TIME/DIV.

Figure 1 - Exploded view of the CES 4708 oscilloscope with all controls numbered. Section A of the panel contains all the vertical controls for two channels. Section B contains the crt and related controls. Section C contains the horizontal sweep controls and section D the Sync and Trigger controls.

INPUT CONNECTORS

Connections are made to the various inputs (CH 1, CH 2, EXT SYNC) through the use of BNC connectors mounted on the 'scope panel. The female panel mounted jack and the male connector and probe cable are shown in Figure 2.

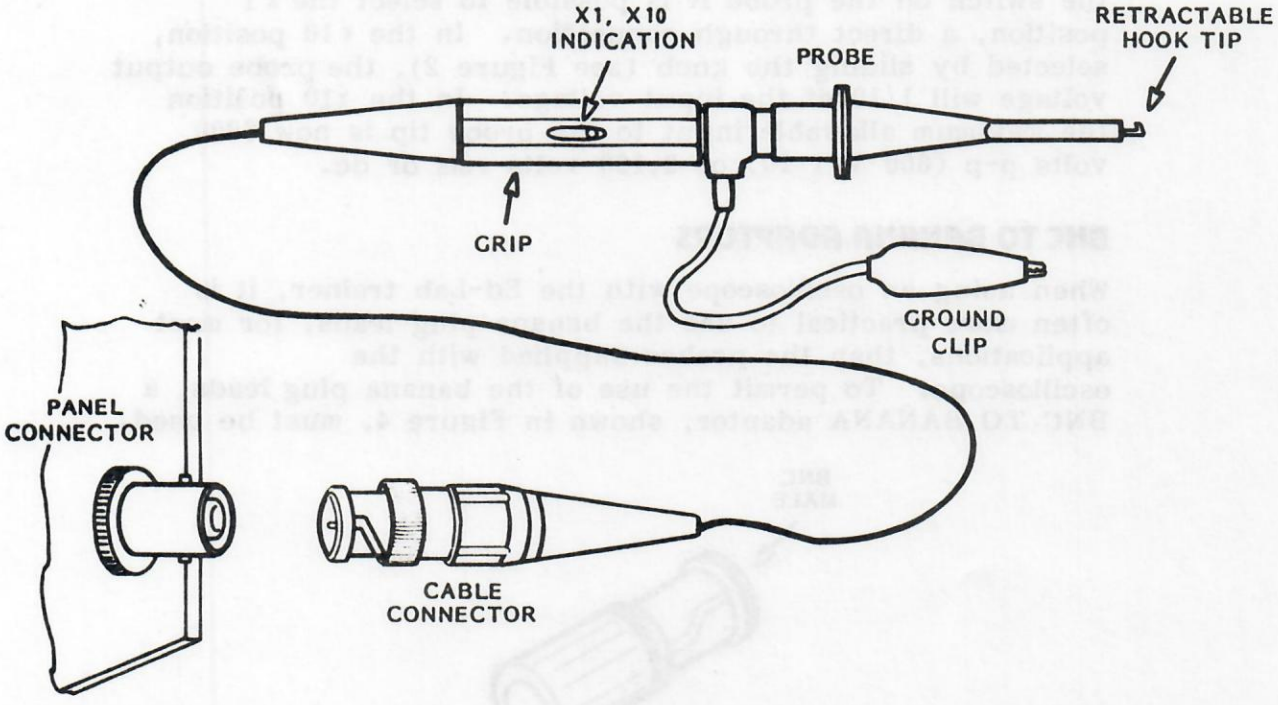


Figure 2 - BNC connector cable and probe for use with the input jacks.

As shown in Figure 2, the male BNC connector is at the end of the oscilloscope probe cable. When attached to the panel connector, the probe end of the cable is then connected to the waveform to be observed as shown in Figure 3.

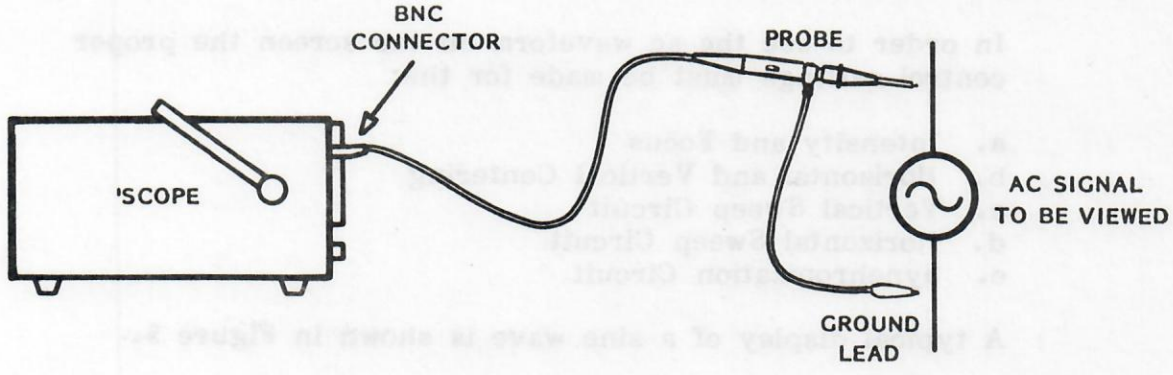


Figure 3 - Oscilloscope input cable connected to an ac signal to be displayed on the crt.

PROBE SWITCH

The probe contains a switch that inserts a voltage divider for the reduction of high voltages. This is necessary when the input is greater then 600 volts p-p or 212 volts rms or dc. Six hundred volts is the maximum allowable voltage that can safely be applied to the CH1 or CH2 inputs. By sliding the switch on the probe it is possible to select the x 1 position, a direct through connection. In the x 10 position, selected by sliding the knob (see Figure 2), the probe output voltage will 1/10 of the input voltage. In the x10 position the maximum allowable input to the probe tip is now 6000 volts p-p (600 V x 10) or 2,120 volts rms or dc.

BNC TO BANANA ADAPTORS

When using an oscilloscope with the Ed-Lab trainer, it is often more practical to use the banana plug leads, for most applications, than the probes supplied with the oscilloscope. To permit the use of the banana plug leads, a BNC TO BANANA adaptor, shown in Figure 4, must be used.

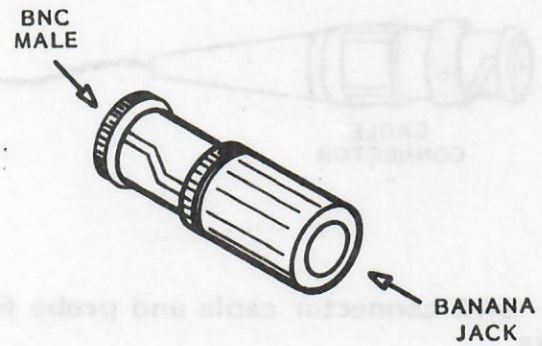


Figure 4 - BNC to BANANA adapter for use with oscilloscopes or any other test equipment.

WAVEFORM OBSERVATION

In order to see the ac waveform on the screen the proper control settings must be made for the:

a. Intensity and Focus
b. Horizontal and Vertical Centering
c. Vertical Sweep Circuit
d. Horizontal Sweep Circuit
e. Synchronization Circuit

A typical display of a sine wave is shown in Figure 5.

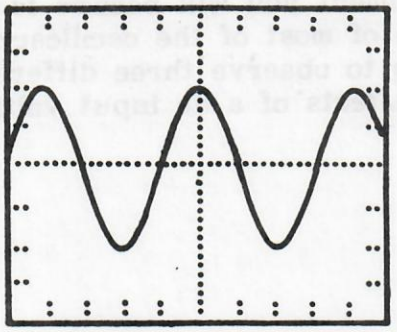
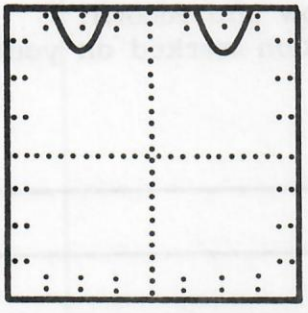
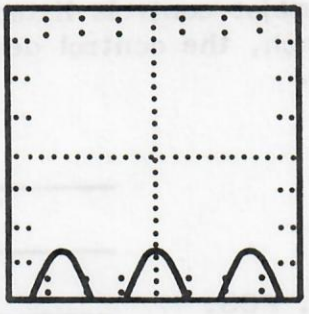


Figure 5 - Proper sine wave display on the oscilloscope screen.

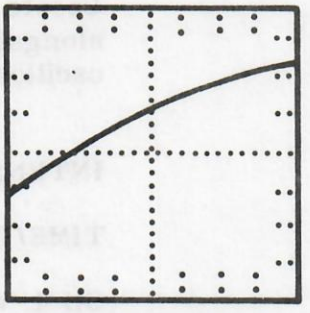
Incorrect displays resulting from improper settings of the Horizontal, Vertical and Sync controls are shown in Figure 6 below.



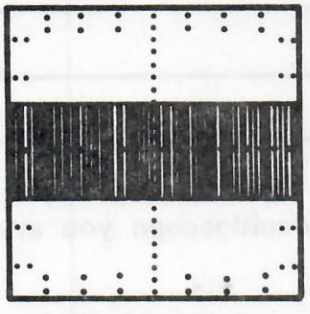
(a) Vertical Centering too high.



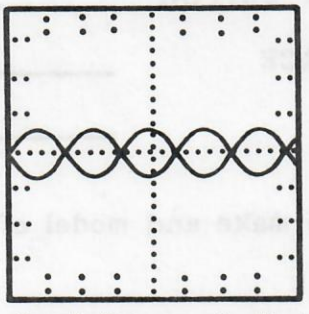
(b) Vertical centering too low.



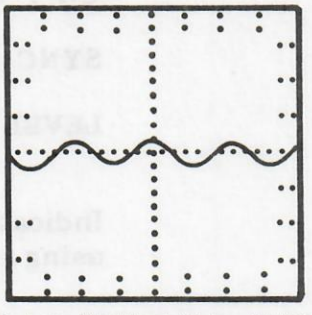
(c) Time/Div too high.



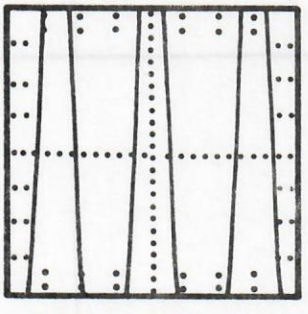
(d) Time/Div too low.



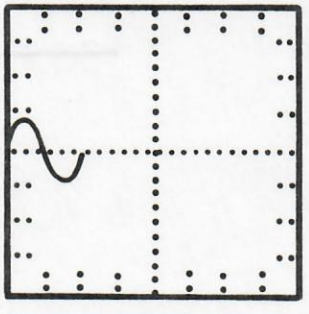
(e) Synch Trigger misadjusted.



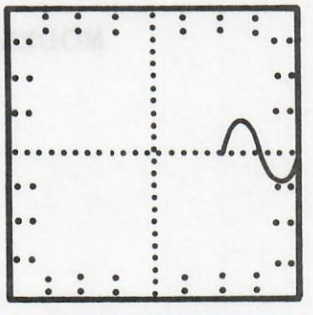
(f) Low Vertical Gain (V/Div).



(g) Excessive Vertical Gain.



(h) Horizontal Centering off.



(i) Horizontal Centering off.

Figure 6 - Typical results of misadjusted oscilloscope controls.

In this experiment you will become familiar with the location and operation of most of the oscilloscope controls. You will use the scope to observe three different waveshapes and to observe the effects of a dc input voltage on the crt trace.

PROCEDURE

1. Obtain a copy of the instruction manual for the oscilloscope you will use for this experiment.

   Locate the major controls listed below and record, alongside each, the control designation marked on your oscilloscope.

   INTENSITY _____

   TIME/DIV _____

   CH 1 VERT. POS. _____

   CH 1 INPUT SWITCH _____

   SYNC SOURCE _____

   LEVEL _____

   Indicate the make and model of the oscilloscope you are using.

   MANUFACTURER _____

   MODEL NO. _____

Count the total number of controls on your oscilloscope. How many are there? _____

Count the total number of inputs on the front panel. How many are there? _____

List the names of these inputs below.

1. _____ 3. _____

2. _____ 4. _____

2. Plug the scope into the power line. Locate the ON-OFF switch and turn the power ON.

3. Allow 40 seconds for the crt filament to warm up.

While waiting, set the following controls as noted.

(11) INTENSITY - Rotate 3/4 of the way clockwise.
(10) FOCUS - Set to mid-point.
(33) HORIZ. POSITION - Set to mid point.
(13) CH 1 VERT. POSITION - Set to mid point.
(28) LEVEL - Push in for AUTO and set to mid point.
(25) VERTICAL MODE - Set to CH 1.
(35) TIME/DIV - Set to 0.1 ms.
(26) AC-GND-DC CH 1 - Set to DC position.
(14) VOLTS/DIV CH 1 - Set to 5.
(31) SOURCE - Set to CH 1 (or INTERNAL on some scopes)
(32) COUPLING - Set to AC.
(27) SLOPE - Set to +.

1.1 FREE RUNNING TRACE

4. When the crt has warmed up, a bright horizontal line will appear on the screen. This line is called a "Free Running Trace" or simply the Trace.

Does the trace appear? _____

Adjust the CH 1 VERTICAL POSITION control so that the trace is properly centered.

If the trace does not appear, increase the INTENSITY control setting to near maximum and recheck the settings of the controls listed on the below.

(33) HORIZ. POSITION
(13) CH1 VERT POSITION
(28) LEVEL (pushed in for AUTO)
(25) VERT MODE (set to CH 1)

1.2 INTENSITY AND FOCUS

5. When the trace has appeared, adjust the INTENSITY (11) and FOCUS (10) controls for a bright, sharp trace. Use the least amount of intensity possible. This will prolong crt life and protect the screen phosphor.

1.3 SINE WAVE OBSERVATION

6. Wire the Ed-Lab 651 Function Generator to the oscilloscope as shown in Figure 7. An external Function Generator can be used if necessary.

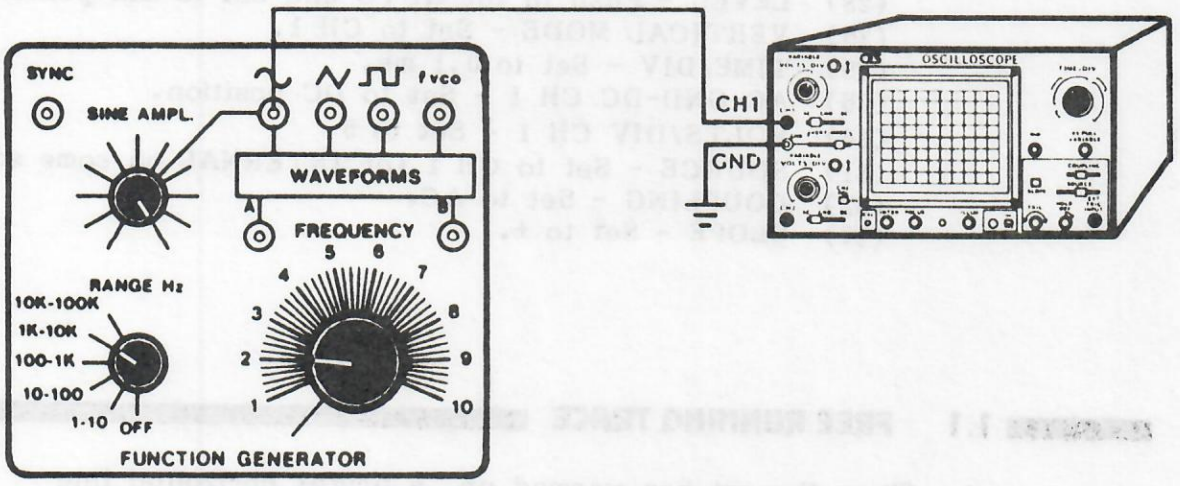


Figure 7 - Function Generator sine wave output and ground connected to the CH 1 input of the oscilloscope; EXPERIMENT.

Connect a "BNC to Banana" adaptor to the CH 1 input jack (16), insert a 2 ft banana plug lead into the CH1 adapter and connect the other end to the sine wave output as shown in Figure 7.

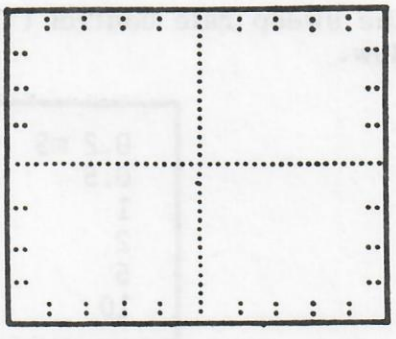
Connect a second 2 ft banana lead between the Ed-Lab 651 ground jacks and the oscilloscope ground jack, also shown in Figure 7.

7. Set the Function Generator controls as listed below for an output of 2 kHz.

RANGE Hz	1 K - 10 K
FREQUENCY	2
SINE AMPL.	Maximum Clockwise

8. Carefully adjust all the controls so that 2 to 3 cycles appear on the screen. The waveform should be steady, not rolling, and should appear as shown earlier in Figure 5.

   Sketch the waveform obtained in the space provided below.



9. Now vary the Frequency control of the Function Generator from 1 to 10 (1 kHz to 10 kHz).

   Count and record the number of sine waves observed on the screen and record them in Table 1 for each frequency setting.

FREQ. (kHz)	NO. OF CYCLES
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

TABLE 1 - Input frequency versus screen display.

10. Return the Function Generator frequency setting to 2 kHz.

    Rotate the TRIGGER LEVEL control over its full range from + to -. Describe the effect.

1.4 INCORRECT SWEEP RATE

11. Change the sweep rate control (TIME/DIV) over the range listed below.

0.2 mS
0.5
1
2
5
10

    Comment on the effect on the screen display.

12. Return the control setting to 0.1 mS/DIV.

13. Now change the sweep rate control over the range in μS listed below.

50 μS
20
10
5
2

Comment on the effect on the screen display.

14. Return the TIME/DIV control setting to 0.1 mS/DIV.

1.5 INCORRECT AMPLITUDE

15. Change the CH 1 VOLTS/DIV control setting over the range listed below.

2
1
0.5
0.2

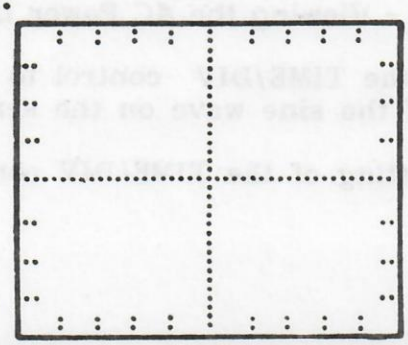
Comment on the effect on the screen display.

Return the CH 1 VOLTS/DIV control setting to 5.

1.6 TRIANGULAR AND SQUARE WAVES

16. Move the CH 1 input lead from the Sine to the Triangle wave output jack (Red) on the Ed-Lab 651.

17. Adjust the LEVEL control for a stable display, if necessary, and draw the screen display in the space provided below.

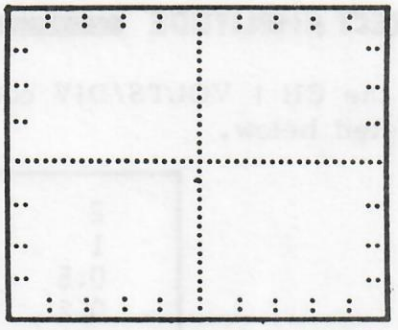


TRIANGULAR WAVE

18. Move the CH 1 input lead to the Square Wave output jack (Yellow) on the Ed-Lab 651.

    Adjust the oscilloscope controls for a stable display. Observe that the vertical traces of the square wave are barely visible. This is normal because the electron beam sweeps up and down so rapidly it does not linger long enough to excite the screen phosphor.

19. Draw the square wave screen display in the space provided below. Draw the vertical traces even though they are barely visible.



SQUARE WAVE

1.7 60 HERTZ POWER LINE SIGNAL

20. Connect the CH 1 input to the AC transformer secondary on the Ed-Lab trainer as shown in Figure 8.

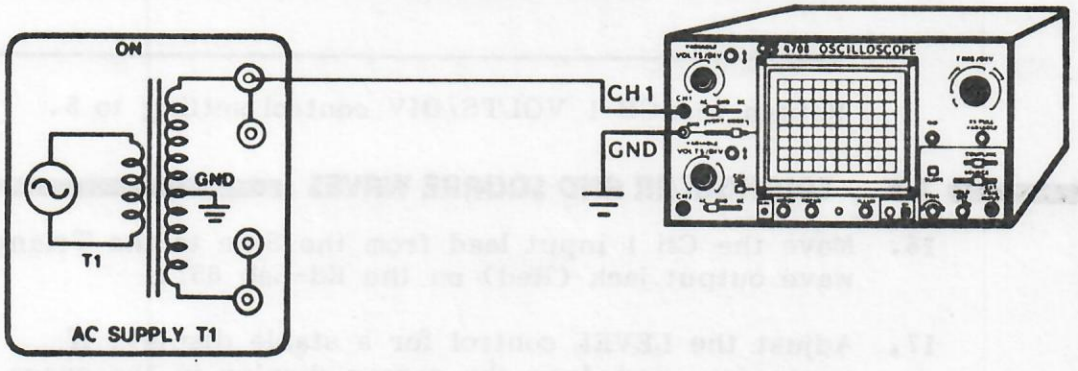


Figure 8 - Viewing the AC Power Line signal; EXPERIMENT.

21. Adjust the TIME/DIV control to produce close to one cycle of the sine wave on the screen.

    What setting of the TIME/DIV control was needed? _____

22. Readjust the TIME/DIV control for a display of two cycles.

    What is the new TIME/DIV control setting? _____

1.8 DC VOLTAGES

In the AC position of the INPUT switch, the dc input does not affect the screen display. In the DC setting of the switch, however, the trace is displaced vertically for a varying dc input voltage. The distance the trace moves is determined by the amount of input voltage and the setting of the VOLTS/DIV switch.

23. Check to see that the listed controls for CH 1 are set as follows.

    (14) VOLTS/DIV 5
    (26) INPUT SWITCH DC

24. Move the CH 1 input lead to the +V1 output.

    Vary the +V1 Voltage Control over its full range and observe the results. Describe it below.

    _____

    _____

    _____

    _____

25. Move the AC-GND-DC switch (26) to the AC position. Vary the +V1 knob, observe the movement of the trace and describe it below.

    _____

    _____

    _____

    _____

    _____

1.9 VOICE INPUT

26. Turn off the Ed-Lab trainer and connect the Microphone/Earphone directly across the CH 1 input as shown in Figure 9.

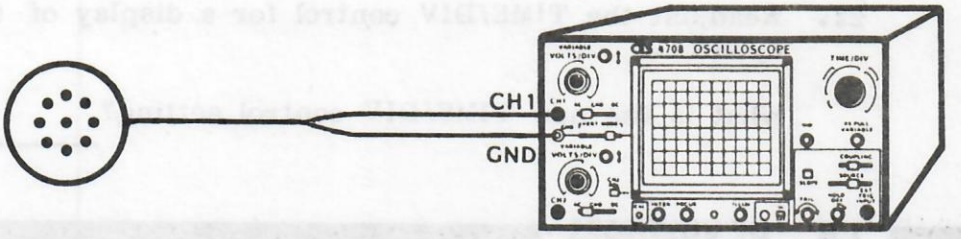


Figure 9 - Sound observation EXPERIMENT.

27. Set the CH 1 VOLTS/DIV switch to 20 mV and the horizontal TIME/DIV switch to 2 mS.

28. Speak into the microphone and observe the sound waveforms. Try whistling softly. What do you conclude?

1.10 STRAY PICK-UP

There is a great deal of electromagnetic radiation floating all around you. The strongest of these signals is that from the 60 Hz power lines and lighting system. A loose lead connected to the CH 1 input can pick up these signals.

29. Remove the microphone and connect a 2 ft lead to the CH 1 input as shown in Figure 10.

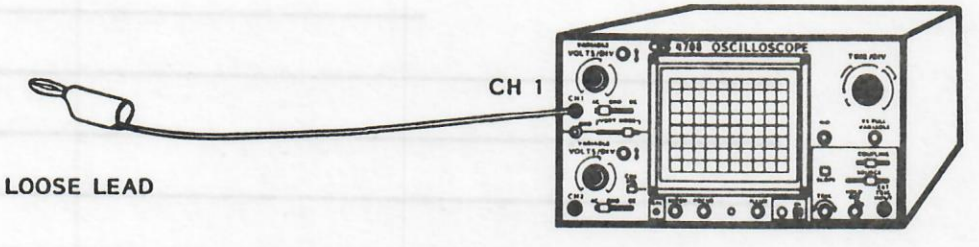


Figure 10 - Stray pick up EXPERIMENT.

The controls are still set as before, VOLTS/DIV at 20 and TIME/DIV at 2 mS.

30. Observe the display. Is there a signal on the screen? _____

Where does it come from? _____

_____

31. Hold the loose end of the lead between your thumb and forefinger. What happens to the display? _____

_____

Why? _____

_____

Because of the stray 60 Hz signal, it is sometimes necessary to use the special input cables provided with the oscilloscope (Figure 2) to prevent unwanted 60 Hz pick up.

CONCLUSIONS

We have learned from this experiment that:

Ac voltage waveforms can be observed on an oscilloscope screen.

The oscilloscope controls can be divided into four basic groups. These are:

CRT DISPLAY CONTROLS
VERTICAL SWEEP CONTROLS
HORIZONTAL SWEEP CONTROLS
SYNC CONTROLS

Oscilloscope input jacks use BNC type connectors.

Oscilloscope input cables have connector probes that contain a voltage divider that drops the input to 1/10 (÷10).

The input probe voltage divider is selectable by a switch on the probe.

A "BNC to Banana" adapter can be used to permit the employment of ordinary banana leads with the scope.

Incorrect settings of the various controls will cause improper screen displays.

Control locations and names vary from oscilloscope to oscilloscope but are fundamentally the same controls.

The TIME/DIV control determines the number of cycles of the observed signal that appears on the screen.

The VOLTS/DIV control determines the height of the screen display.

The INTENSITY control determines the brightness of the screen display.

The TRIGGER control, when properly set, eliminates horizontal movement or "floating" of the display.

DC input voltages will not affect the screen display if the input switch is set at AC.

DC input voltages will cause the screen trace to be displaced vertically when the input switch is set at DC. The greater the DC voltage the greater the vertical displacement.

ASSIGNMENT

Answer the following True False questions.

1. The Intensity control on an oscilloscope is the same as the Brightness control. _____

2. The VOLTS/DIV switch controls the vertical amplitude of the screen display. _____

3. In order to measure a dc voltage, the vertical input switch must be set at GND. _____

4. In order to observe a large input voltage it is desirable to place the cable probe switch in the x1 position. _____

5. Banana plug leads should not be used to connect an oscilloscope into a circuit to observe a waveform. _____

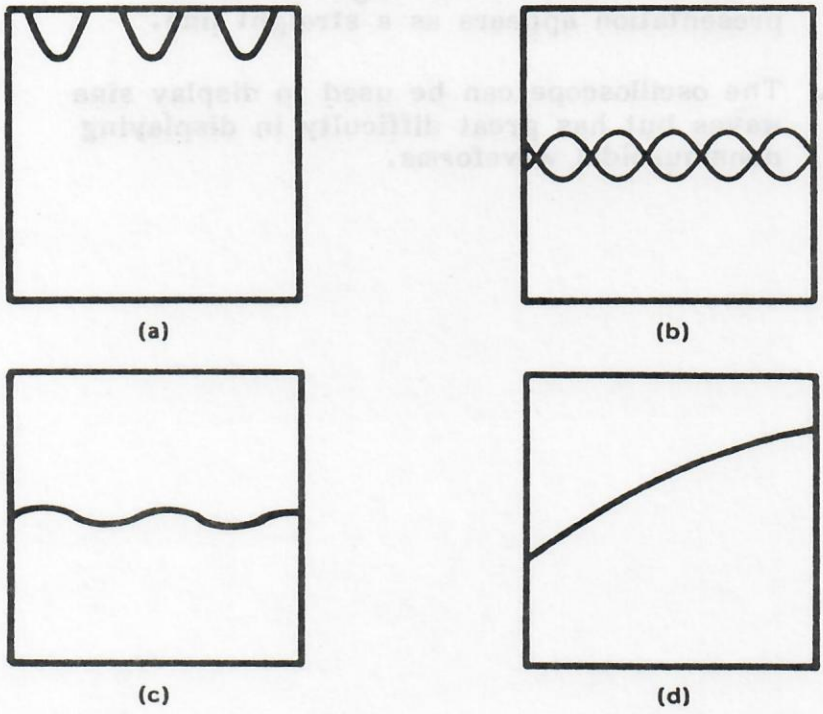


Figure 11 refers to questions 6 to 9.

6. The display in Figure 11(a) is due to a misadjusted Vertical Position control. _____

7. The display in Figure 11(b) is due to an improperly set AC-GND-DC input switch. _____

8. The display in Figure 11(c) is due to an improperly set Trigger control. _____

9. The display in Figure 11(d) is due to an improperly adjusted TIME/DIV control. ____

10. As the time setting of the TIME/DIV control is made smaller, more cycles of the observed waveform appear on the screen. ____

11. The input jacks available on the front panel of most oscilloscopes are CH 1 and CH 2 inputs and EXTERNAL INTENSITY. ____

12. When a bright line appears on the crt screen running from left to right it is called a "Free Running Trace." ____

13. As the frequency of the input signal to CH 1 is increased the number of cycles appearing on the screen decreases. ____

14. When the horizontal sweep rate, as set by the TIME/DIV switch is too high the screen presentation appears as a straight line. ____

15. The oscilloscope can be used to display sine waves but has great difficulty in displaying nonsinusoidal waveforms. ____

KEY TERMS

1. BNC CONNECTOR

   A "bayonet type" connector designed for 50 ohm coaxial cable. It has a quick connect/disconnect feature and locks into position.

2. BRIGHTNESS CONTROL

   A potentiometer mounted on the front panel of an oscilloscope used to control the intensity of the crt display.

3. CENTERING CONTROL

   A potentiometer mounted on the front panel of an oscilloscope used to position the beam both vertically and horizontally.

4. INTENSITY CONTROL

   Another term for the Brightness Control, used to control the brightness of the display on the crt screen.

5. MICROPHONE

   A device that changes sound waves into equivalent electrical impulses.

6. POSITION CONTROL

   Another term for the Centering Control, used to center the screen display horizontally and vertically in an oscilloscope.

7. TIME/DIV SWITCH

   The front panel control on an oscilloscope that controls the time it takes the crt electron beam to move one division (one cm), horizontally.

8. VERTICAL MODE SWITCH

   Located on the front panel of an oscilloscope, this control determines if CH 1 or CH 2 signals are displayed, or both. On some oscilloscopes, it can be used to add the two vertical signals.

9. VOLTS/DIV CONTROL

   The front panel control on an oscilloscope that determines the amount of input voltage to CH 1 or CH 2 required to deflect the beam one division (one cm) vertically.

Dual Trace Oscilloscope Operation

2

OBJECTIVES

When you finish this experiment, you will be able to:

1. Set up a scope for dual trace operation.
2. Display both the "before" and "after" signals on the scope screen simultaneously.
3. Measure the phase displacement between two signals.
4. Test the operation of chop and alternate sweep modes.
5. Use the Variable controls, CH 2 Invert switch, Slope switch and the External Sync source to properly display a waveform.

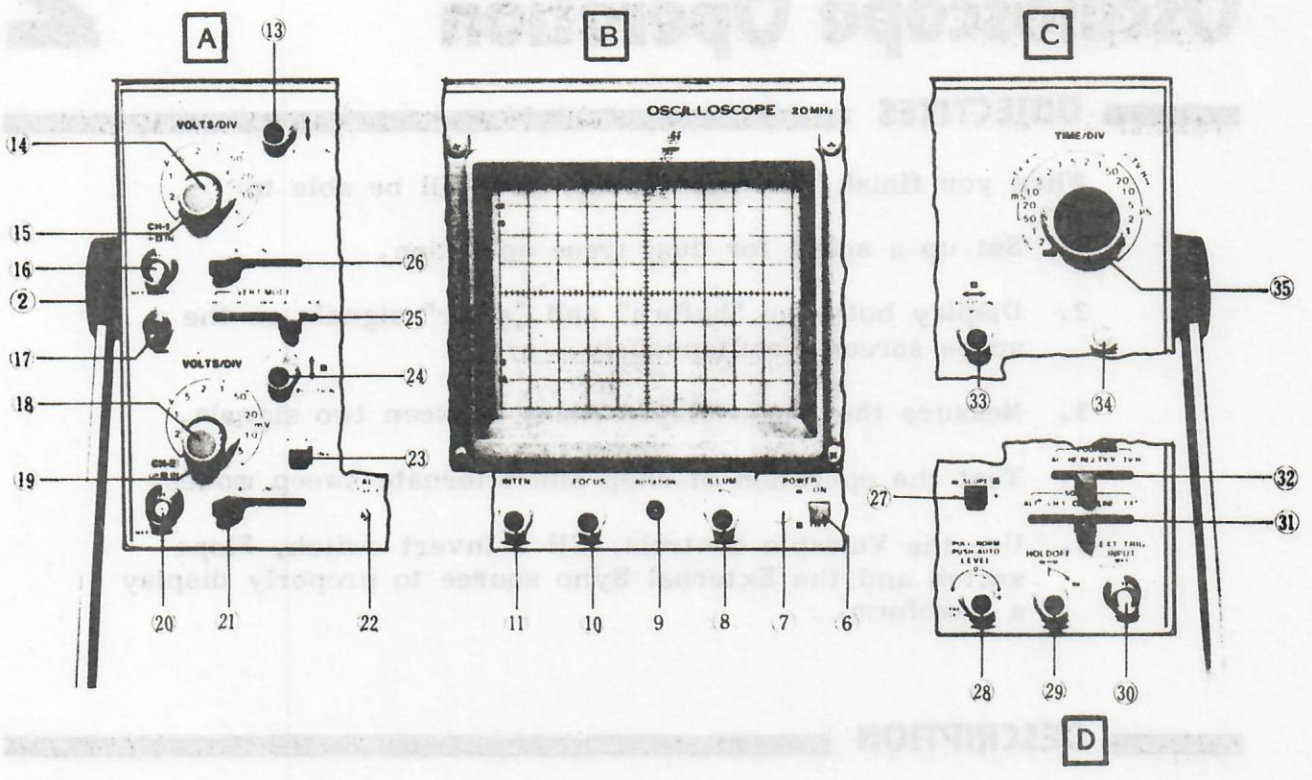
DESCRIPTION

The operation of the dual trace oscilloscope was explained earlier in Information Sheet 1. Single trace operation was tested in Experiment 1, Waveform Observation. In this experiment you will test dual trace operation and operate all the special controls not yet used. These are:

VERTICAL MODE Switch
VARIABLE Controls
CH 2 INVERT Switch
SLOPE Switch
x5 MAGNIFIER Switch

A picture of the CES 4708 oscilloscope is shown again in Figure 1 to help you locate the necessary controls.

2—DUAL TRACE OSCILLOSCOPE OPERATION



⑥ POWER ⎓/⏦ON/OFF

⑧ ILLUM

⑨ ROTATION ⊘

⑩ FOCUS

⑪ INTEN

⑬ ↕ (CH-1)

⑭ VARIABLE (CH-1)

PULL x 10

⑮ VOLTS/DIV (CH-1)

⑯ CH-1 IN

⑱ VARIABLE (CH-2)

PULL x 10

⑲ VOLTS/DIV (CH-2)

⑳ CH-2 IN

㉑ AC-GND-DC (CH-2)

㉒ CAL 0.5Vp-p

㉓ CH-2 POL.

㉔ ↕ (CH-2)

㉕ VERT MODE

㉖ AC-GND-DC (CH-1)

㉗ SLOPE

㉘ LEVEL

PULL NORM/PUSH AUTO

㉙ HOLDOFF

㉚ EXT TRIG INPUT

㉛ SOURCE

㉜ COUPLING

㉝ ↔

㉞ TIME VARIABLE

PULL x 10 MAG

㉟ TIME/DIV.

Figure 1 - Exploded view of the CES 4708 oscilloscope with all controls numbered. Section A of the panel contains all the vertical controls for two channels. Section B contains the crt and related controls. Section C contains the horizontal sweep controls and section D the Sync and Trigger controls.

PROCEDURE

1. Connect the inputs to both CH 1 and CH 2 as shown in Figure 2 below.

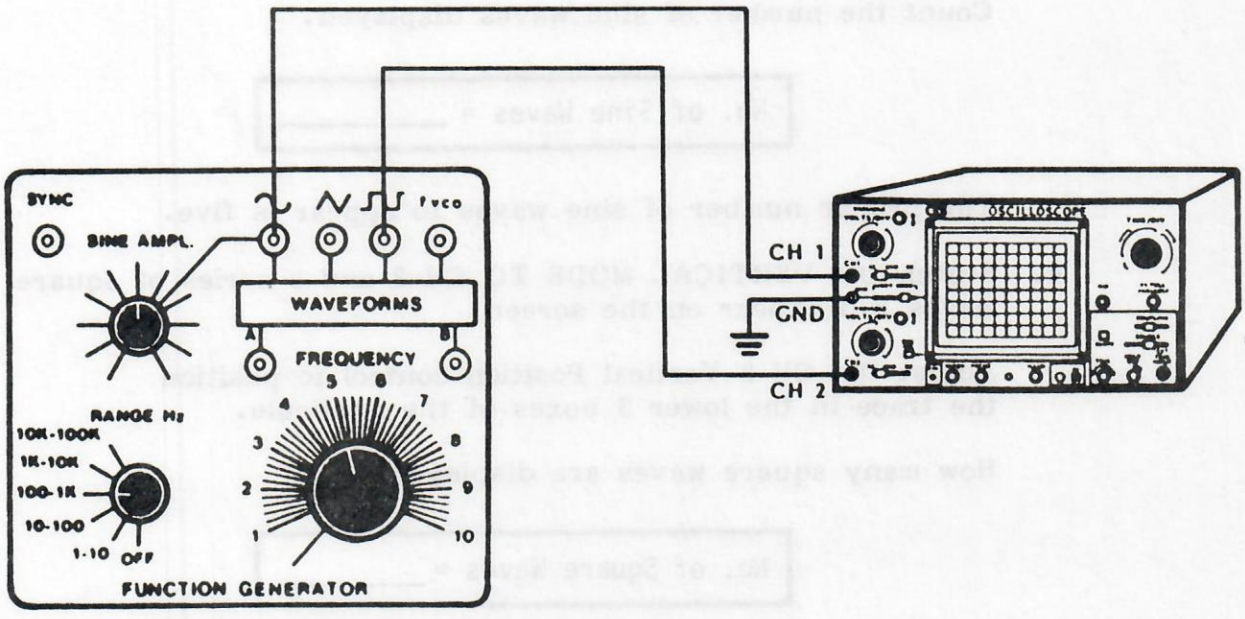


Figure 2 - Connection of scope to Function Generator; EXPERIMENT.

2. Set the controls for the scope and Function Generator as follows:

OSCILLOSCOPE CONTROLS

CH 1 and CH 2 VOLTS/DIV at 2
CH 1 and CH 2 INPUT SWITCH at DC
VERTICAL MODE to CH 1
SYNC SOURCE to CH 1
TIME/DIV to 1 mS
LEVEL to AUTO and at mid-point

FUNCTION GENERATOR CONTROLS

FREQUENCY to 5
RANGE HZ to 100 - 1K
SINE AMPL. to mid rotation.

This provides a 500 Hz sine wave output.

3. Apply power to both the oscilloscope and trainer and, after allowing warm-up time, adjust the Intensity, Focus and Centering controls so that the display is positioned in the upper three boxes of the graticule.

   Count the number of sine waves displayed.

   No. of Sine Waves = _____

   The proper number of sine waves to appear is five.

4. Switch the VERTICAL MODE TO CH 2 and a series of square waves will appear on the screen.

   Adjust the CH 2 Vertical Position control to position the trace in the lower 3 boxes of the graticule.

   How many square waves are displayed?

   No. of Square Waves = _____

   The proper number of square waves to appear is five.

2.1 DUAL TRACE OPERATION

5. Move the VERTICAL MODE switch setting from CH 2 to CHOP.

   Describe the new screen display.

   _____

   _____

   _____

6. Using the Vertical Position control, move the CH 1 trace to the bottom of the screen so that it overlaps the square wave.

   Compare the frequencies of the two signals. Are they the same and WHY?

   _____

   _____

   _____

   _____

   Reposition the CH 1 Position control so that CH 1 is back at the top and CH 2 at the bottom.

2.2 VARIABLE CONTROLS

7. A very important application for dual trace operation is to enable the technician to observe the effect of circuit components upon a signal. It permits a "before" and "after" observation.

   Wire the circuit shown in Figure 3 below.

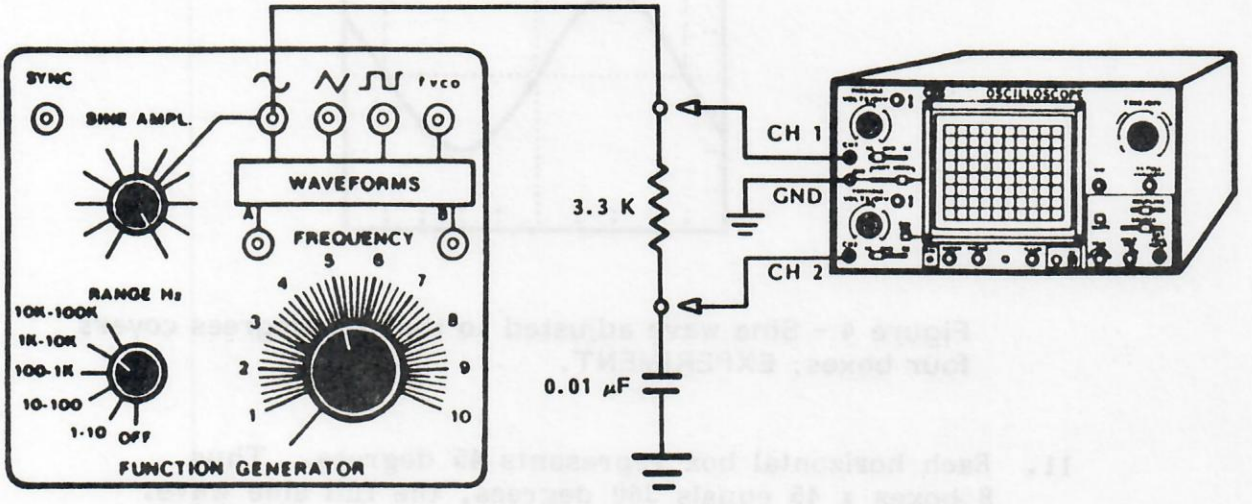


Figure 3 - Dual trace display EXPERIMENT.

8. Set the Function Generator to 5 kHz with full sine wave output and the scope controls as listed below.

CH 1	VOLTS/DIV	2 V
CH 1	INPUT SW	AC
CH 2	VOLTS/DIV	1 V
CH 2	INPUT SW	AC
TIME/DIV		20 μS
SYNC SOURCE		CH 1
VERT MODE		CH 1

9. Adjust the VARIABLE knob of the CH 1 VOLTS/DIV control so that the sine wave covers exactly 6 boxes peak to peak.

   Use the Vertical Position control so that the sine wave is set at 3 boxes above and 3 boxes below the zero line on the graticule.

10. Adjust the VARIABLE control of the TIME/DIV control so that half of the sine wave covers 4 boxes horizontally.

    The resulting display should appear as in Figure 4.

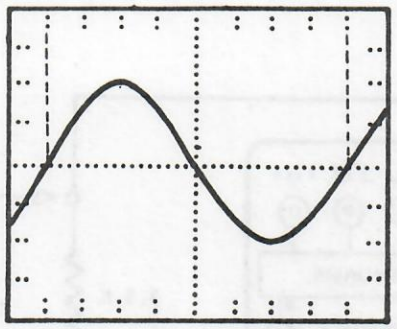


Figure 4 - Sine wave adjusted so that 180 degrees covers four boxes; EXPERIMENT.

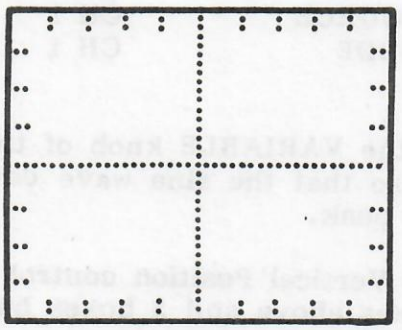
11. Each horizontal box represents 45 degrees. Thus 8 boxes x 45 equals 360 degrees, the full sine wave.

12. Switch from CH 1 mode to the CH 2 mode.

    Adjust the sine wave for an amplitude of 6 boxes, centered on the zero line, using the CH 2 VARIABLE control and the CH 2 Vertical Position control.

13. Switch from CH 2 mode to ALT (Dual Trace) and observe both traces.

    Draw both traces below, clearly marking each trace, using different colors or using one dotted and one dashed line.



14. Count the number of boxes that separate the two waveforms at the point where they pass through the zero line.

Since each box represents 45 degrees, the angular difference between the both waves is equal to

Angle = (No. of Boxes)(45)

Angle = ( )(45) = _____ degrees

This represents the amount of delay incurred by charging the capacitor (CH 2) as compared to the original input voltage (CH 1).

2.3 CH 2 INVERT SWITCH

15. Return the circuit to that shown in Figure 2.

Reset the Function Generator for 500 Hz.

Set the oscilloscope controls as follows:

CH 1 and CH 2 VARIABLE back to calibrate
CH 1 and CH 2 Volts/Div at 2
CH 1 and CH 2 Input Switches at AC
VERTICAL MODE to CHOP
TIME/DIV to 0.5 mS

16. Observe the CH 2 square wave. Is the first half cycle positive or negative going?

_____

Press the CH 2 INVERT switch and observe the first half cycle. Is it still the same?

_____

_____

The CH 2 INVERT switch has reversed the waveform. This is called a 180 degree shift and will be discussed in detail in a later experiment.

Restore the CH 2 INVERT switch to its normal position (out).

2.4 SLOPE SWITCH

The slope switch determines if the display synchronizes on the positive or negative slope of the input signal.

17. Depress the SLOPE switch; observe and describe the effect on the display.

_____

_____

_____

Be sure to observe that both inputs have shifted to start the sweep on the negative half cycle.

Return the Slope switch to the + position.

2.5 EXTERNAL SYNC

18. Move the SYNC SOURCE switch from CH 1 to EXTERNAL (EXT).

How does this affect the screen display? _____

_____

_____

19. Connect a 2 ft lead from the Sync output of the Function Generator to the EXT SYNC (or EXT TRIG) input of the scope as shown in Figure 5.

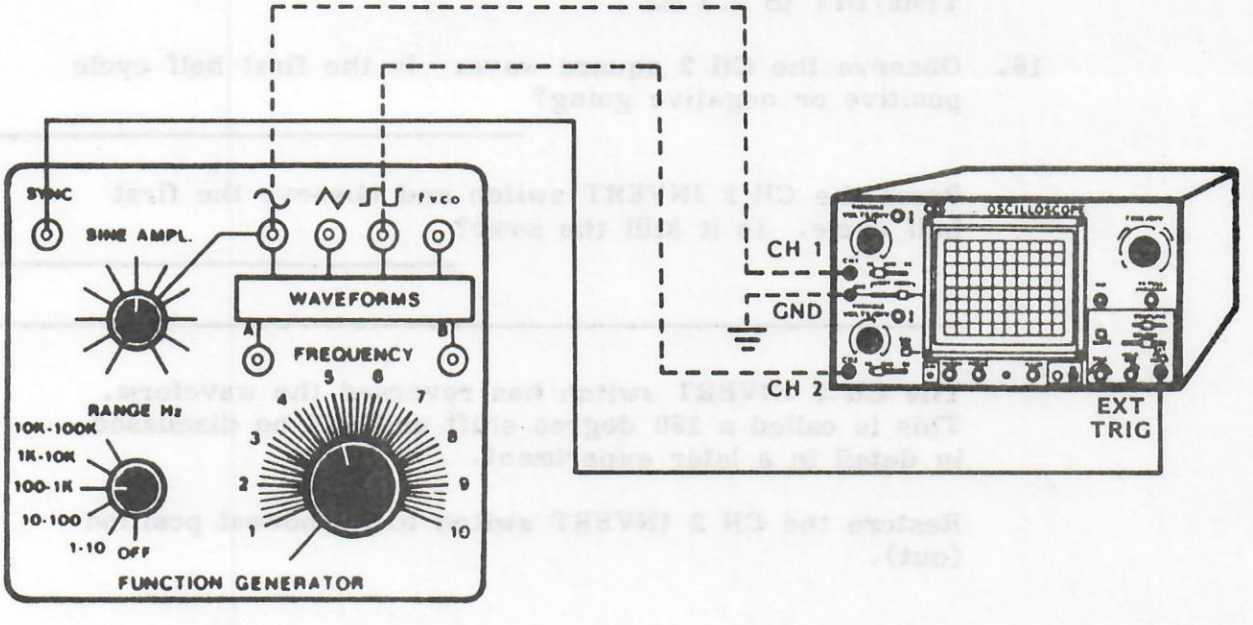


Figure 5 - External Sync EXPERIMENT.

Describe the immediate effect upon the screen display.

20. Adjust the LEVEL control over its full rotation and observe and record in Figure 6(a) the arc over which the display remains locked in.

(a) (b)

Figure 6 - Sync range with external (a) and internal (b) sources; EXPERIMENT.

21. Switch back to CH1 Sync and adjust the LEVEL control over its full range observing the arc over which sync is held. Record it in (b) of Figure 6.

Which provides the wider range of sync?

The reason for this is that, in this instance, the External Sync input signal is much stronger than the Internal Sync source and so holds over a wider range.

22. **Remove the CH 2 input lead from the Square wave output. Attach an alligator clip adaptor to the lead and connect the clip to the 0.5 V PP Calibrate signal on the oscilloscope panel (Figure 7). The Calibrate signal is explored in detail in the next experiment.**

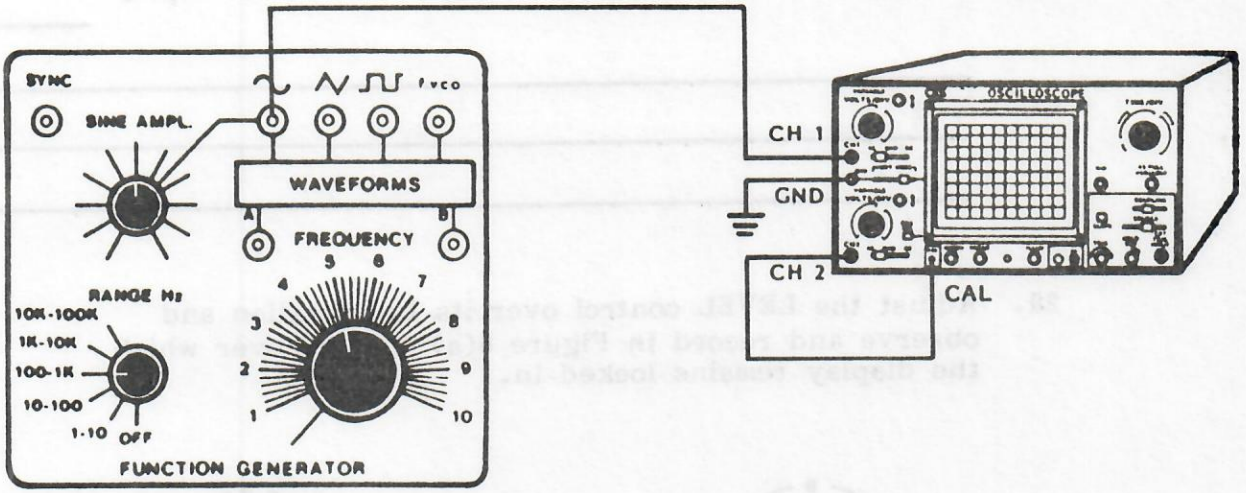


Figure 7 - CH 2 input connected to Cal output; EXPERIMENT.

Shift the CH 2 VOLTS/DIV switch from 2 to 0.2.

23. Observe the screen. What has happened to the CH 2 display?

_____

_____

_____

24. Switch the Sync Source to CH 2. What has happened?

_____

_____

_____

The horizontal sweep circuit of the scope can synchronize on one frequency only, CH 1 or CH 2, but not both at the same time.

2.6 MAGNIFIER OPERATION

25. Reconnect the CH 2 input to the Function Generator square wave and set the CH 2 gain back to 2 V.

Set the oscilloscope controls as follows to observe a single square wave on the screen.

VERT MODE SWITCH	CH 2
SYNC SOURCE	CH 2
TIME/DIV	0.2 mS

Position the display so that the retrace from peak + to peak - is in the center. (Note that it is barely visible.)

26. Connect two 0.01 μF capacitors in series (for a value of 0.005 μF) and wire them across the square wave output as shown in Figure 8. Set switch SA DOWN

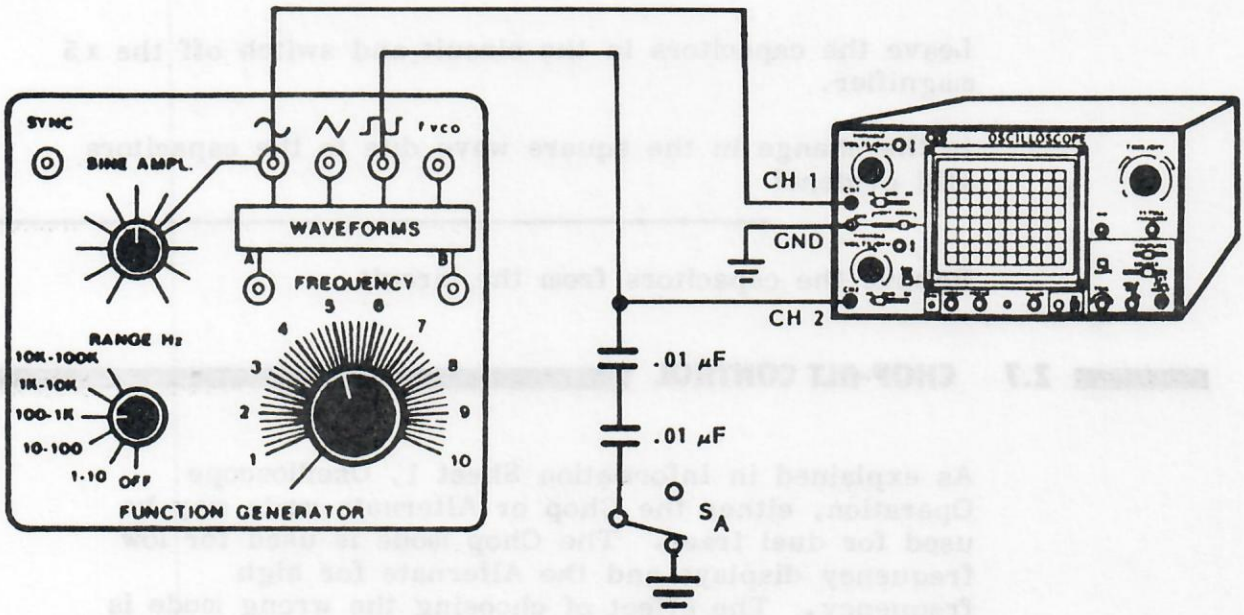


Figure 8 - Addition of capacitors across the square wave output; EXPERIMENT.

27. Observe the screen display as you connect the capacitors across the generator output.

Note that it affects only one part of the square wave. What is that part?

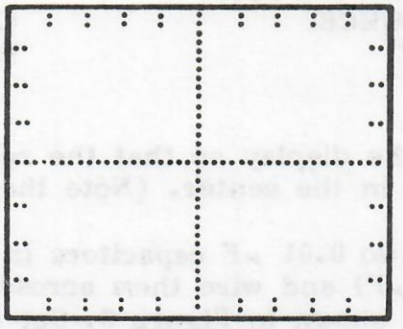
_____

_____

28. Now switch on the x5 MAGNIFIER and observe the vertical portions of the trace.

Remove the capacitor connection and reconnect it several times by moving Switch SA UP and DOWN while observing the display.

Draw the display with the capacitors in the circuit and the x5 magnifier ON.



Leave the capacitors in the circuit and switch off the x 5 magnifier.

Is the change in the square wave due to the capacitors still evident?

Remove the capacitors from the circuit.

2.7 CHOP-ALT CONTROL

As explained in Information Sheet 1, Oscilloscope Operation, either the Chop or Alternate mode may be used for dual trace. The Chop mode is used for low frequency displays and the Alternate for high frequency. The effect of choosing the wrong mode is shown in the following steps.

29. Recheck the controls listed below and set them as indicated.

TIME/DIV Control	1 mS
CH 1 AND CH 2 VOLTS/DIV	2
VERT MODE	CHOP
SYNC SOURCE	CH 1
INPUT FREQUENCY	500 HZ

Position the sine wave in the upper 3 boxes and the square wave in the lower 3 boxes.

30. Switch from the CHOP mode to the ALT mode.

What happens to the screen display?

31. Place the Vertical Mode switch back to CHOP and increase the input frequency from 500 Hz to 5 kHz.

Reset the Time/Div to 50 μS.

Describe the screen display. (If the chop is not visible adjust the Frequency control slightly until it is.)

Pull out the x5 magnifier to see the chop more clearly.

32. Switch the mode setting from CHOP to ALT. What happens to the display?

CONCLUSIONS

We have learned from this experiment that:

It is possible to view two separate signals on a dual trace oscilloscope simultaneously.

The VARIABLE controls permit precise adjustment of horizontal and vertical displacement not possible with the fixed switch positions of the Vertical and Horizontal controls.

It is possible to use the dual trace display to observe "before" and "after" signal waveforms.

14—DUAL TRACE OSCILLOSCOPE OPERATION

The dual trace scope can be used to measure the phase difference between two voltages.

The INVERT switch will introduce a 180 degree shift in the CH 2 screen presentation only.

The SLOPE switch determines if the display starts on the negative or positive slope of the vertical input signals. When changed from + to - or - to + the CH 1 and CH 2 displays shift.

It is possible to synchronize the screen display from an external source fed to the EXT SYNC input terminal.

The MAGNIFIER switch expands the screen presentation by a factor of 5 or 10.

The CHOP-ALT positions of the VERTICAL MODE switch can be used to select the method of dual trace operation that does not cause flicker or show gaps in the display.

ASSIGNMENT

Answer the following True-False questions.

1. If you wish to adjust the height of a waveform to precisely 4 boxes p-p but the 2 V/DIV setting of the VOLTS/DIV switch is too small and the 1 V/DIV setting is too high, you must use the 2 V/DIV setting and adjust the height with the VARIABLE control. ____

2. Once a VARIABLE control is switched ON, the calibration is off and that circuit cannot be used for measurements. ____

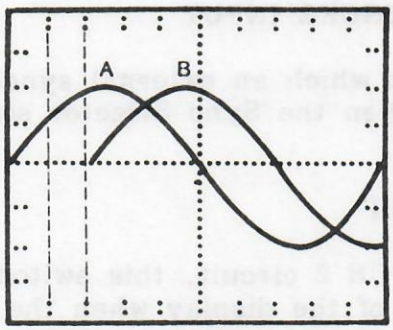


Figure 9 refers to questions 3 to 6.

3. For the display shown in Figure 9, each division represents 36 degrees. ____

4. There is a 72 degree difference between signals A and B. ____

5. Signal B is appearing before or earlier than signal A. ____

6. If the amplitude of signal B is increased the difference, in degrees, between each signal would also increase. ____

7. The SLOPE control determines if the display starts with the negative or positive half of the cycle for both CH 1 or CH 2 inputs. ____

8. The CH 2 INVERT switch causes only the CH 2 signal to undergo a 180 degree shift. ____

9. If the CH 1 or CH 2 inputs are different frequencies neither channel can be synchronized. ____

10. The MAGNIFIER control expands the screen image by 5 times both horizontally and vertically. ____

KEY TERMS

1. CALIBRATE POSITION

   The setting for the oscilloscope VARIABLE controls that validates the calibration for the CH 1, CH2 Vertical V/DIV and Horizontal TIME/DIV controls.

2. EXTERNAL SYNC

   Sync Source switch setting to select the synchronization signal from an external source, outside of the oscilloscope.

3. EXTERNAL TRIGGER INPUT

   The terminal to which an external synchronizing signal is connected when the Sync Selector switch is set to External Sync.

4. INVERT SWITCH

   Usually in the CH 2 circuit, this switch allows a 180° phase reversal of the display when the switch is depressed.

5. MAGNIFIER x5 SWITCH

   When this switch is on, the horizontal is amplified (expanded) five times more than normal to enable small irregularities in a waveform to be examined more closely.

6. SLOPE SWITCH

   Selects the half cycle, + or -, on which the screen display will start.

7. SYNC SOURCE SWITCH

   Switch that selects the source of the synchronizing signal from CH 1, CH 2, CH1-2 alternate, Power Line or External.

8. VARIABLE CONTROLS

   Controls that allow continuous adjustment of the vertical gain (CH 1 and CH 2) and the horizontal time base.

Oscilloscope Measurements 3

OBJECTIVES

When you finish this experiment, you will be able to:

1. Measure peak-to-peak voltages using the oscilloscope.
2. Measure the period of a waveform.
3. Convert the period measurement of a waveform to frequency.
4. Measure frequency with a Frequency Counter (Optional).
5. Use the oscilloscope calibrate signal, CAL, to check horizontal and vertical calibration.
6. Measure DC voltages with an oscilloscope.

ADDITIONAL EQUIPMENT

Frequency Counter, CES 4024 or equal (Optional).

DESCRIPTION

When measuring ac with meters of any type, the scales are usually calibrated in rms and are accurate for sine waves only. There are times when it is necessary to measure nonsinusoidal ac voltages such as square, ramp and trapezoid waveforms. This cannot be done accurately with a meter and it is done using an oscilloscope. In addition to observing nonsinusoidal voltages, the oscilloscope can be used to measure the period of an ac waveshape and from the period, it is possible to calculate the frequency from 1/t. There are some meters designed to measure the "true rms" ac voltage for any waveshape.

VOLTAGE MEASUREMENT

Peak, peak-to-peak, dc voltages, and the voltage at any point in a complex waveshape can easily and accurately be measured using the triggered oscilloscope (either single or dual trace). The following descriptions are valid for a typical oscilloscope and may not exactly correspond to the oscilloscope you are using.

The VOLT/DIV switches for both channels, CH 1 and CH 2, have settings from 5 V/DIV down to 5 mV/DIV. These se figures represent the amount of voltage required to sweep the electron beam vertically a distance of 1 centimeter. One centimeter is the spacing of one major division on the crt screen as shown in Figure 1. Each major division of 1 cm is further divided into 5 parts, each equal to 0.2 cm. Note the five minor divisions in center lines, both vertical and horizontal, of the graticule on the oscilloscope.

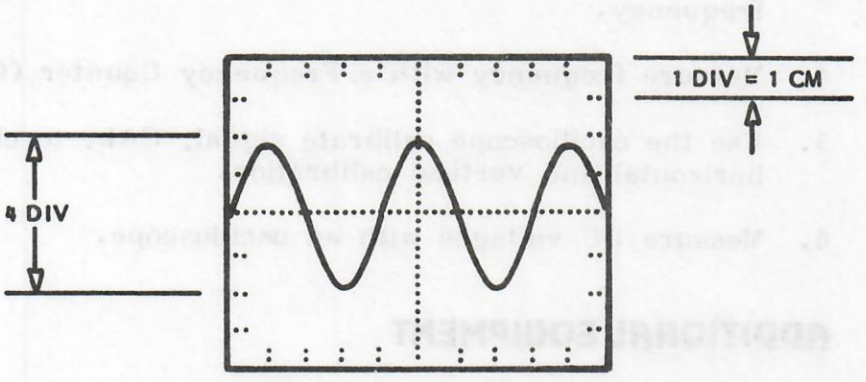


Figure 1 - An ac waveform that covers 4 divisions vertically.

If the waveform, as shown, covers 4 divisions vertically and the VOLTS/DIV switch is set at 2, the peak-to-peak amplitude of the waveform is:

$$V_{p\text{-}p} = (\text{No. of Div})(\text{VOLTS/DIV})$$

$$= (4)(2)$$

$$\boxed{V_{p\text{-}p} = 8 \text{ Volts}}$$

NOTE: To be certain that the voltage measurements are accurate, two things must be checked. These are:

1. If a probe is used, the probe switch should be set at x1 (times 1) for the voltage calculation to be correct.

   If the probe switch is set at x10 (times 10) the calculated voltage based on the vertical displacement must be multiplied by 10.

2. The CH 1 and CH 2 VARIABLE controls must be set at the CALIBRATED position, usually fully clockwise. If the VARIABLE control of the channel you are using to make the voltage measurement is not clicked into the Calibrated position, the voltage calculation will be incorrect.

PERIOD MEASUREMENT

The period of any ac waveform is easily measured with a triggered oscilloscope. The TIME/DIV switch is calibrated typically from 0.2 S/DIV to 0.2 μS/DIV (microseconds per division). These values represent the time required to sweep the electron beam horizontally a distance of 1 cm or one major division on the crt screen as shown in Figure 2.

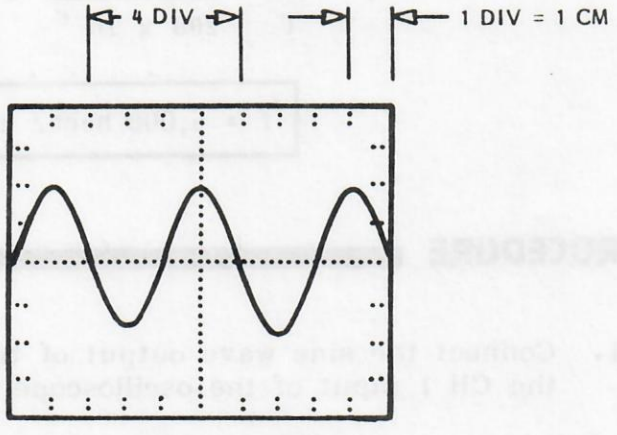


Figure 2 - Measurement points to determine the period of one cycle of ac.

Given a sine wave that covers precisely 4 cm horizontally, as shown in Figure 2, and a TIME/DIV switch setting of 50 μS, the period is:

$$\text{PERIOD} = (\text{No. of Div})(\text{TIME/DIV Setting})$$

$$= (4)(50\ \mu\text{S})$$

$$\boxed{\text{PERIOD} = 200\ \mu\text{S}}$$

NOTE: If the TIME/DIV VARIABLE control is not set in the CALIBRATED position, the Period measurement is invalid.

FREQUENCY MEASUREMENT

We must perform a calculation to convert the period measurement to frequency.

The formula used is:

$$\text{frequency (f)} = \frac{1}{\text{period (t)}}$$

Thus, for a period of 200 μS, from the above example, the frequency is:

$$f = \frac{1}{t} = \frac{1}{200 \times 10^{-6}} = \frac{1{,}000{,}000}{200}$$

f = 5,000 hertz or Hz

PROCEDURE

1. Connect the sine wave output of the Function Generator to the CH 1 input of the oscilloscope as shown in Figure 3.

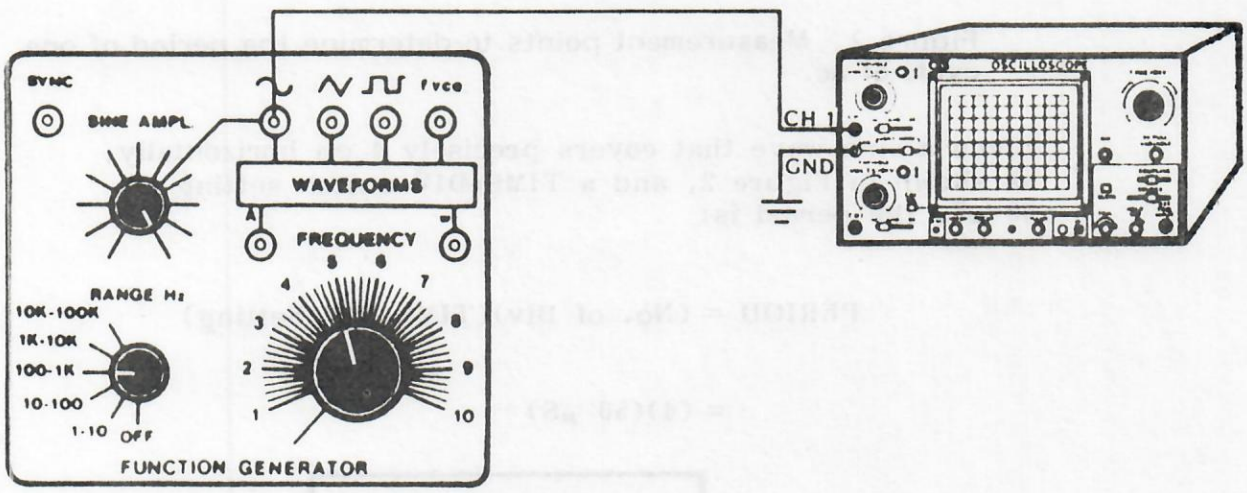


Figure 3 - Sine wave input to the oscilloscope; EXPERIMENT.

2. Set the controls as follows:

Function Generator Settings for 500 Hz

RANGE Hz = 100 - 1 K
FREQUENCY = 5
SINE AMPL. = Maximum Clockwise

Oscilloscope Settings

VERT MODE	CH 1
CH 1 VOLT/DIV	2
CH1 INPUT SWITCH	DC
TIME/DIV	0.5 mS
SYNC SOURCE	CH 1
VARIABLE CONTROLS	CALIBRATED POSITION

Adjust the TRIGGER/LEVEL control for a stable display. If the display should be greater than 8 divisions vertically, shift the CH 1 VOLTS/DIV switch from 2 to 5 V.

3.1 DETERMINING AMPLITUDE

3. Adjust the CH 1 VERT POSITION control so that the negative peak, (A) in Figure 4, is precisely on a horizontal line marking as shown.

Adjust the HORIZONTAL POSITION control so that the positive peak, (B) in Figure 4, is on the center vertical line marking as shown.

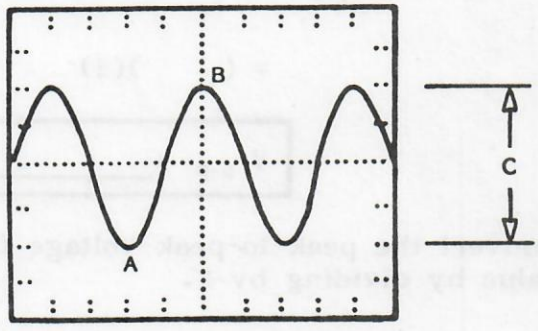
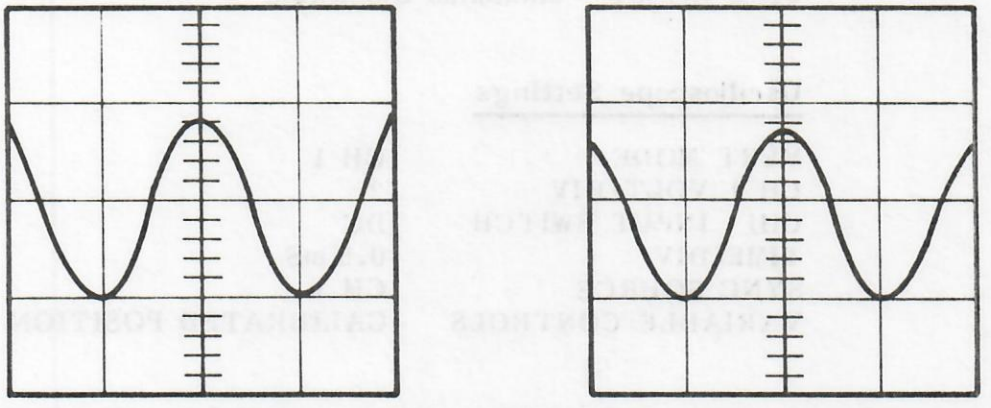


Figure 4 - Position adjustment on the screen; EXPERIMENT.

4. Read the number of vertical divisions covered by the sine wave shown on the crt. Recall that each major division is divided into 5 minor divisions of 0.2 cm each. See the examples in Figure 5.



(a) 1.8 DIVISIONS (b) 1.7 DIVISIONS

Figure 5 - Fractional readings on the vertical scale.

Enter the number of the vertical divisions, below, covered by the sine wave.

VERTICAL DIVISIONS = _____ DIV

5. Multiply the number of vertical divisions by the VOLTS/DIV control setting to get the the peak-to-peak voltage

$$V_{p\text{-}p} = (\text{No. of Div.})(\text{VOLTS/DIV})$$

$$= (\quad)(2)$$

$V_{p\text{-}p}$ = _____ V

6. Convert the peak-to-peak voltage from step 5 to the peak value by dividing by 2.

$$V_{pk} = \frac{E_{p\text{-}p}}{2}$$

$$= \frac{(\quad)}{2}$$

V_{pk} = _____ V

7. Convert the peak voltage to rms by multiplying V_{pk} by 0.707.

$$V_{rms} = V_{pk} \ (0.707)$$

$$V_{rms} = (\qquad)(0.707)$$

V_{rms} = _____ V

3.2 AC METER RMS READING

8. Set the ac voltmeter to the 5 volt range and connect it across the output of the Function Generator as shown in Figure 6.

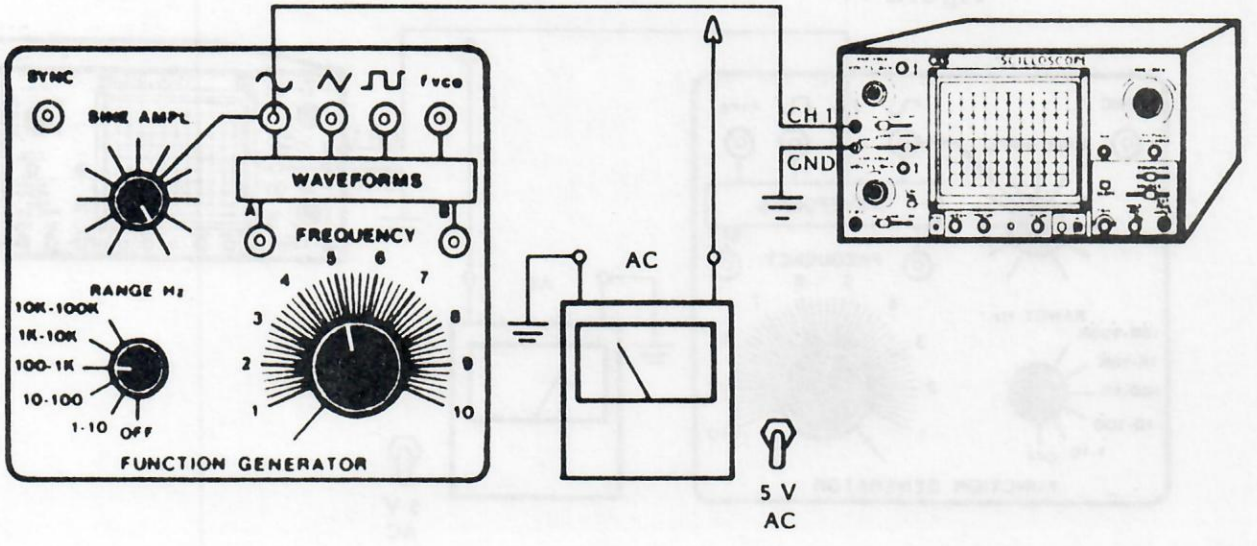


Figure 6 - Measuring the rms output of the Function Generator with the panel meter; EXPERIMENT.

Record the rms meter reading below.

$V_{rms\ MEAS.}$ = _____ V

How close is the meter reading to the value calculated in step 7?

_____

_____

Several conclusions may be drawn from the above. These are:

a. The oscilloscope can be used to measure peak, peak-to-peak and, by calculation, the rms voltage of a sine wave.

b. It is quicker to measure the rms voltage with a meter.

c. The maximum rms output from the Function Generator is approximately 4.5 volts.

3.3 MEASURING NONSINUSOIDAL VOLTAGES

9. Connect the ac voltmeter (5 V range) to the square wave output of the Function Generator as shown in Figure 7.

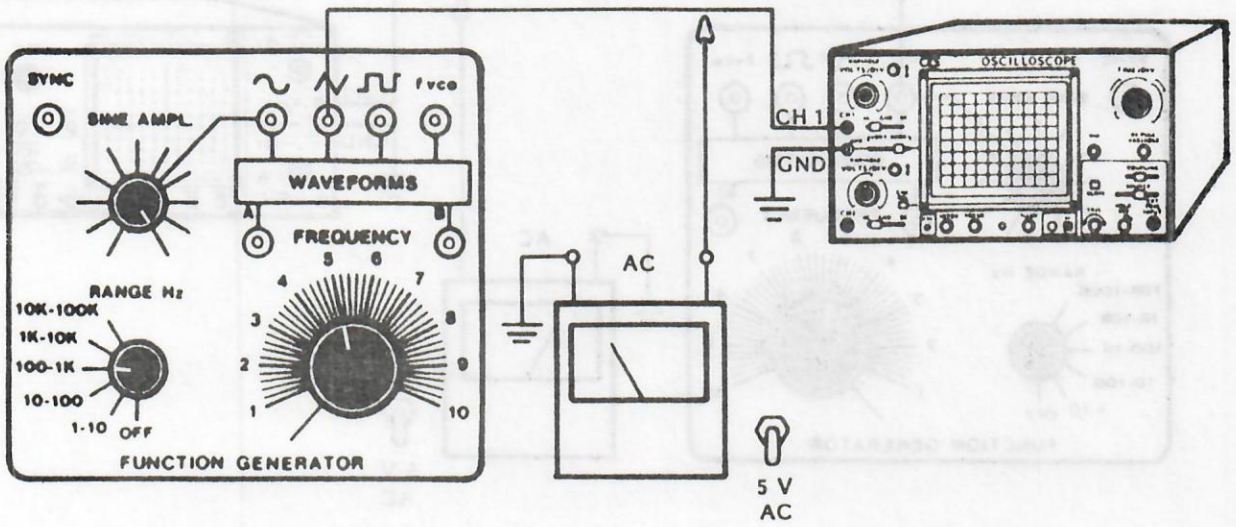


Figure 7 - Measuring the triangle wave output voltage.

Record the meter reading below.

$V_{ac\ triangle\ wave}$ = _____ V

This is not an rms reading because the input is not a sine wave and thus is meaningless.

10. Connect the CH 1 input of the scope to the triangle wave output, measure the peak-to-peak voltage and record it below. The peak-to-peak voltage is a valid quantity.

$V_{p\text{-}p\ triangle\ wave}$ = _____ V

V_{rms} = _____ V

3.4 PERIOD MEASUREMENT

The time duration or PERIOD of a waveform can be measured with the scope using the calibration of the TIME/DIV switch.

11. Disconnect the CH 1 input lead from Triangle output and connect it to the Sine Wave output of the Function Generator as shown in Figure 8.

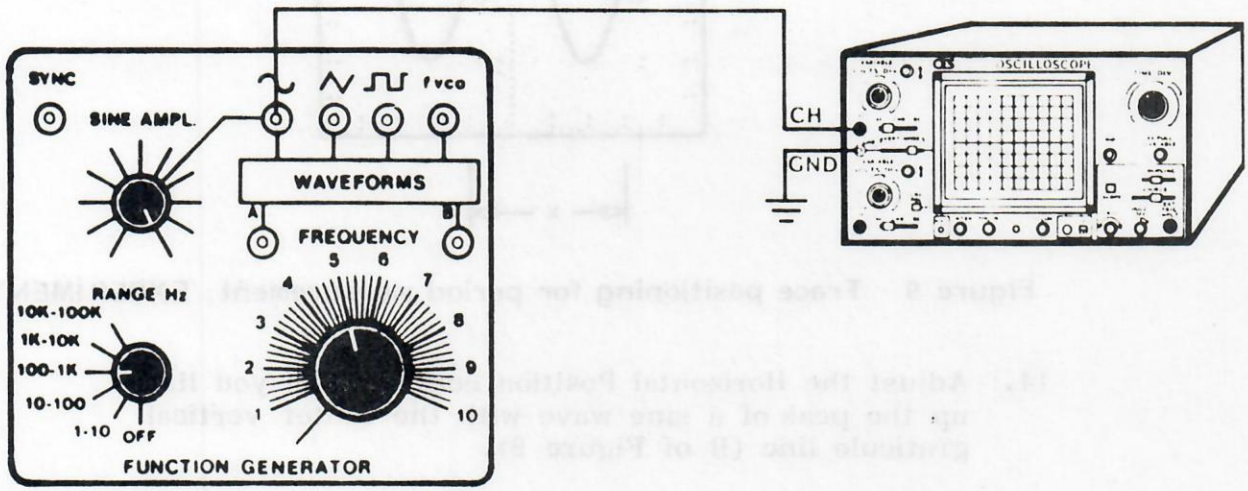


Figure 8 - Test set up to measure Period; EXPERIMENT.

12. Set the Function Generator for full sine wave output at 500 Hz.

Set the Oscilloscope controls so that three sine waves appear (2 1/2 will show). The control settings are:

CH 1 VOLTS/DIV	2 V
CH 1 INPUT SWITCH	DC
VERT MODE	CH 1
SYNC SOURCE	CH 1
TIME/DIV	0.5 mS
SLOPE	+

13. You can determine the time length or period of the wave by measuring time from positive peak to positive peak (A to B of Figure 9) or middle to middle (C to D). The peaks, however, are rounded and you could get a slightly inaccurate reading using A and B.

Using the CH 1 Vertical Position control, align the trace so that it covers an equal number of divisions above and below the center horizontal graticule line as shown in Figure 9.

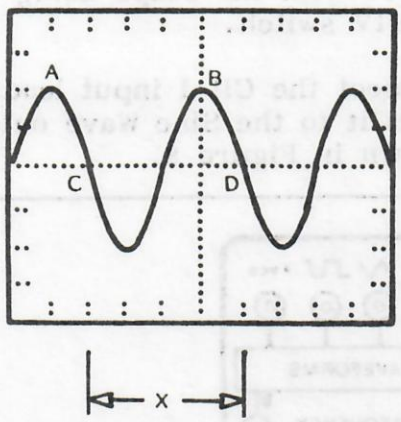


Figure 9 - Trace positioning for period measurement; EXPERIMENT.

14. Adjust the Horizontal Position control until you line up the peak of a sine wave with the center vertical graticule line (B of Figure 9).

15. To calculate the PERIOD, count the number of divisions the waveform on the oscilloscope covers to complete 360 degrees and enter the count below to within 0.1 divisions horizontally (X in Figure 9).

No. of Divisions = _____

16. Calculate the period using the formula

PERIOD = (No. of Div)(TIME/DIV Setting)

= ( )( )

PERIOD (t) = _____

3.5 FREQUENCY CALCULATION

17. To calculate the frequency (f) of a waveshape once the period (t) is known, use the formula:

$$f = \frac{1}{t}$$

Calculate the frequency for the period calculated in step 16.

$$f = \frac{1}{(\text{no. of div})(0.5 \times 10^{-3})}$$

$$= \frac{1}{(\quad)}$$

f = _____ Hz

Does the calculated frequency equal the Function Generator output of 500 Hz?

_____

3.6 FREQUENCY COUNTER (OPTIONAL)

A Frequency Counter is an instrument that measures frequency by counting the number of cycles that occur during a precise time period. It repeats the count every half or one second and provides a read-out on a digital indicator.

You may construct a frequency counter in the Digital portion of this course but for now, use a commercial unit if one is available.

18. Connect a Digital Frequency Meter to the Function Generator output as shown in Figure 10.

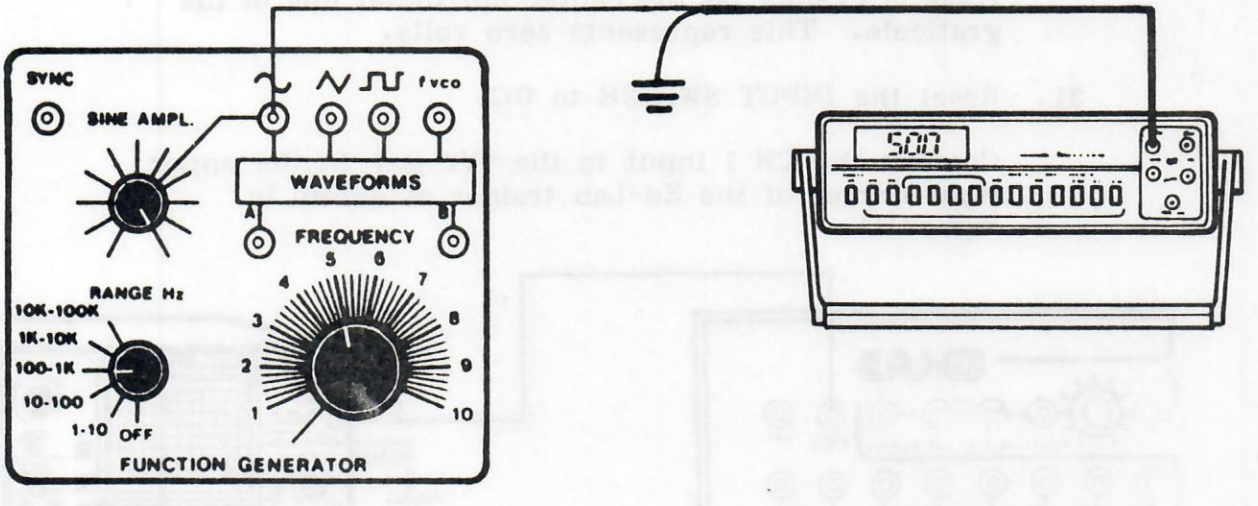


Figure 10 - Frequency counter EXPERIMENT.

19. Allow a few seconds for the reading to stabilize and record the frequency below.

Counter Reading _____ Hz

Does the counter frequency reading agree with the Oscilloscope measurement and the Function Generator dial setting? _____

_____

3.7 DC MEASUREMENTS WITH SCOPE

It is possible and sometimes convenient to measure dc with the oscilloscope. The same graticule calibration is used and the only precaution that must be observed is that the VERTICAL INPUT switch must be on DC. This switch, the VERT INPUT, may be placed in the GND position first to allow adjustment of the trace to the zero position and be reset to DC to read the input voltage.

20. Set the oscilloscope controls as listed below.

CH 1 VOLT/DIV	5 V
CH 1 INPUT SWITCH	GND
VERT MODE	CH 1
TIME/DIV	1 mS or higher
SYNC SOURCE	CH 1

Set the CH 1 VERTICAL POSITION control so that the trace is exactly on the center horizontal line of the graticule. This represents zero volts.

21. Reset the INPUT SWITCH to DC.

Connect the CH 1 input to the +V2 jack in the upper right corner of the Ed-Lab trainer as shown in Figure 11.

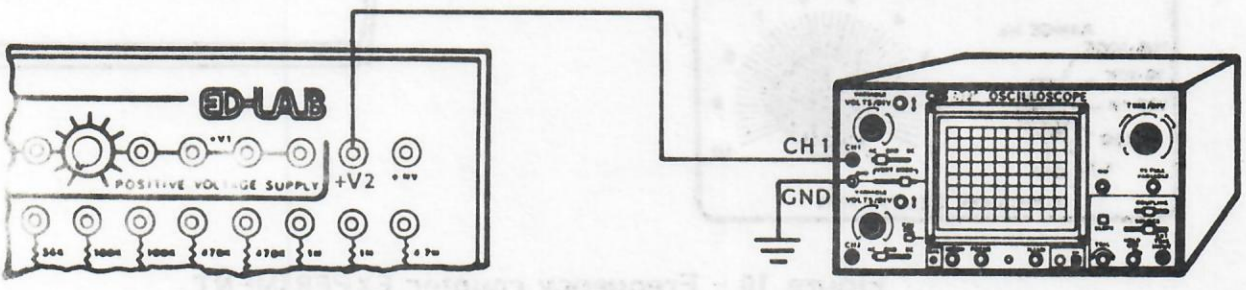


Figure 11 - DC voltage level measurement EXPERIMENT.

22. Count the number of divisions the trace is displaced to an accuracy of 0.1 divisions and record the results below.

VERTICAL DIVISIONS = _____ DIV

In which direction did the trace move, up or down? _____

23. Multiply the number of vertical divisions by the VOLTS/DIV control setting to obtain the dc voltage.

$$V_{dc} = (\text{No. of Div.})(\text{VOLTS/DIV})$$

$$= (\quad)(\quad)$$

V_{dc} = _____ V

24. Move the CH 1 input lead to the -V3 jack of the Ed-Lab trainer and observe the scope trace.

Describe the movement of the scope trace with the -V3 input.

_____

_____

_____

3.8 SCOPE CALIBRATION CHECK

Most oscilloscope manufacturers provide a CALIBRATION voltage that is accessible on the front panel. The CES 4708 oscilloscope has a calibration output (terminal labeled (22) in Figure 1 in Experiments 15 and 16).

This Calibrate signal is 0.5 volts peak-to-peak at 1 kHz and is used to check both the horizontal and vertical calibration accuracy.

25. Connect the CH 1 input to the CALIBRATE terminal as shown in Figure 12.

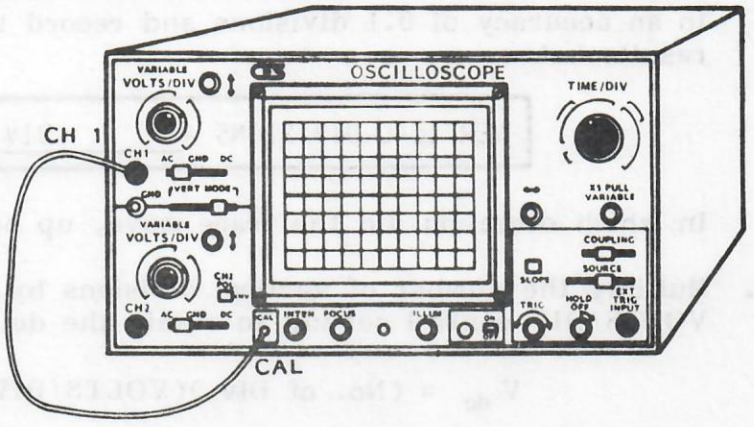


Figure 12 - Calibration check of CH 1; EXPERIMENT.

26. Adjust the scope controls as follows:

CH 1 VOLTS/DIV	0.1 V
VERTICAL MODE	CH 1
SYNC SOURCE	CH 1
TIME/DIV	0.5 mS

27. Count the number of divisions of vertical displacement and record them below.

VERTICAL DIVISIONS = _____

Calculate the peak-to-peak voltage.

$V_{p\text{-}p}$ = (No. of Div.)(VOLT/DIV)

= ( )(0.1)

$V_{p\text{-}p}$ = _____ Volts

Is the CH 1 voltage calibration correct? _____

28. Check the calibration of CH 2 using the same procedure. Remember to reset the Vertical Mode and Sync Source switches back to CH 1.

Is the calibration of CH 2 correct? _____

29. The horizontal TIME BASE is checked using the 1 kHz square wave as follows:

    Position the trace so that a square wave begins on a vertical graticule line.

    Count the number of boxes covered by a full square wave and record it below.

    HORIZONTAL DIVISIONS = _____

30. Calculate the period and frequency.

    PERIOD = (No. of Div.)(TIME/DIV)

    = ( )(0.5)

    PERIOD = _____ mS

    $$f = \frac{1}{t}$$

    $$f = \frac{1}{(\quad)}$$

    f = _____ Hz

31. For a more accurate test of the time base, switch the TIME/CM control to 0.1 mS. and check the period of 1/2 cycle.

    Is the period of 1/2 cycle precisely 0.5 mS? _____

3.9 60 Hz CALIBRATION TEST

If an oscilloscope does not provide a Calibrate source, it is possible to use a 60 Hz signal from the power line to check the horizontal time base only. The power companies maintain very careful control of frequency and so the 60 Hertz is extremely reliable.

32. Connect the CH 1 input to the T1 transformer secondary on the Ed-Lab trainer panel as shown in Figure 13.

Reset the TIME/DIV switch to 2 mS.

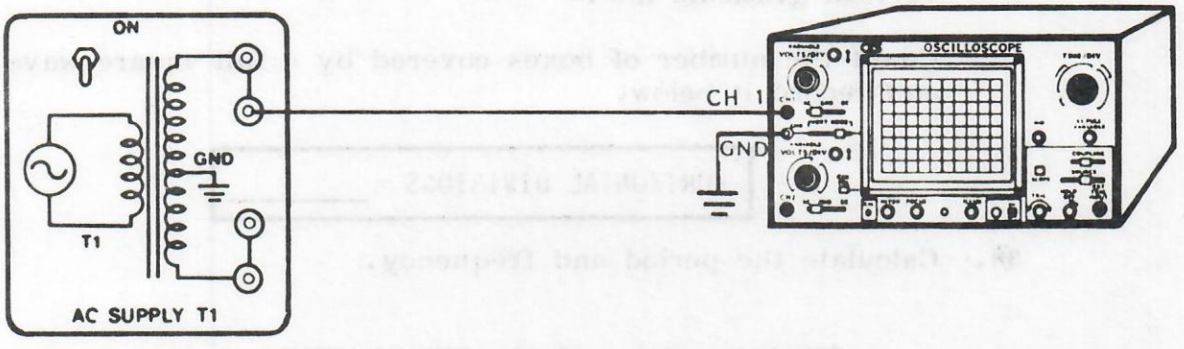


Figure 13 - Calibration check using 60 Hz; EXPERIMENT.

33. Adjust the centering controls so that the display is properly centered for a period measurement.

Count and record the number of horizontal divisions (to 0.1 accuracy) covered by a complete cycle.

60 Hz Divisions = _____

Calculate the period of the waveform and convert it to frequency.

Power Line Period = (No. of Div)(TIME/DIV)

= ( )(2 mS)

Power Line Period = _____ mS

$$\text{Power Line Frequency} = \frac{1}{\text{t in seconds}}$$

$$= \frac{1}{(\quad S)}$$

$$= \frac{1}{(\quad)}$$

POWER LINE FREQUENCY = _____ Hz

How close is your answer to 60 Hz? _____

_____

If there is an error do you think it is the power line frequency that is off? _____

_____

_____

_____

CONCLUSIONS

AC panel meters are calibrated in rms unless marked otherwise.

AC panel meters are calibrated for sine waveforms only. Other waveshapes cannot be measured with the meter with good accuracies.

Nonsinusoidal waveforms can be measured using calibrated trigger scopes.

Voltage is measured by counting the number of vertical divisions covered by the trace and multiplying by the VOLTS/DIV setting.

Each major division of the graticule is 1 cm.

Each minor division of the graticule is 0.2 cm.

When measuring voltage on CH 1 or CH 2 the VARIABLE controls must be in the CALIBRATE position.

When using the probe while making voltage measurements, the probe switch setting, x1 or x10, must be taken into account. Thus:

$$V_{p\text{-}p} = (\text{No. of DIV})(\text{VOLTS/DIV})(\text{PROBE SW setting})$$

The PERIOD of a waveform is measured by counting the number of horizontal divisions covered by a single cycle and multiplying that number by the setting of the TIME/DIV control.

$$\text{PERIOD} = (\text{No. of Div.})(\text{TIME/DIV setting})$$

When measuring period, the TIME/DIV VARIABLE control must be in the CALIBRATE position.

The period measurement can be converted to frequency from $f = 1/t$ in sec.

A digital frequency meter can be used to read frequency directly on a digital read-out.

Most oscilloscopes have a Calibration Test Signal, usually 0.5 V p-p at 1 kHz.

The oscilloscope can be used to measure dc as well as ac voltages.

The 60 Hz power line signal can be used to check the horizontal time base accuracy.

ASSIGNMENT

Answer the following Multiple Choice questions.

1. The ac scales on a VOM are useable for the direct measurement of:

   a. frequency.
   b. rms voltage.
   c. peak voltage.
   d. peak-to-peak voltage.

2. The ac VOM is calibrated to measure:

   a. sine waves.
   b. sine and square waves.
   c. sine or triangular waves.
   d. all of the above.

3. Each major division marked off on the oscilloscope graticule is equal to:

   a. 0.2 cm.
   b. 2 volts.
   c. 5 volts.
   d. 1 cm.

4. The correct formula to determine the peak voltage of the display on the scope screen, is:

   a. $\dfrac{\text{(VOLTS/DIV)(No. of Vert Div)}}{\text{Probe Setting}}$

   b. $\dfrac{\text{(VOLTS/DIV)(No. of Horiz Div)}}{\text{Probe Setting x 2}}$

   c. $\dfrac{\text{(VOLTS/DIV)(No. of Vert Div)(Probe Setting)}}{2}$

   d. None of the above.

5. When measuring voltage with the oscilloscope you must set the:

   a. Vert Mode at CHOP.
   b. CH 1 VARIABLE control to mid-point.
   c. CH 1 VARIABLE control to CAL.
   d. TIME/DIV VARIABLE control to CAL.

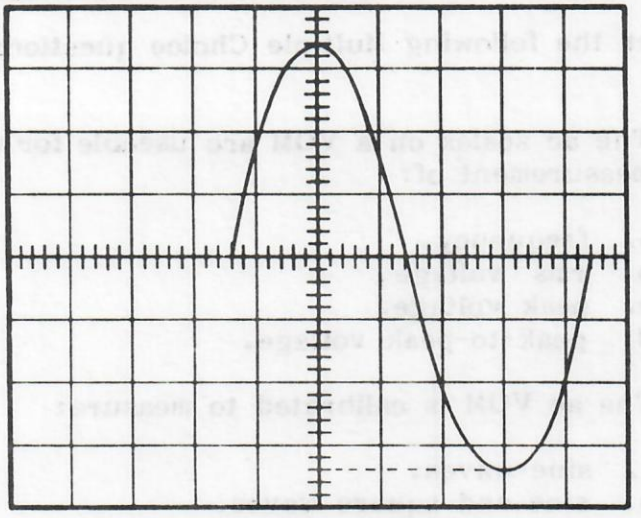


Figure 14 refers to questions 6 to 8.

6. The waveform displayed in Figure 14 is obtained with the VOLTS/DIV set at 20 mV and the TIME/DIV set at 5 μS. The peak-to-peak voltage equals:

   a. 0.136 V
   b. 0.136 mV.
   c. 36 mV.
   d. 136 V.

7. The rms voltage indicated by the display in Figure 14 with the VOLTS/DIV set at 5 V and the TIME/DIV set at 10 μS is closest to:

   a. 34 V.
   b. 17 V.
   c. 12 V.
   d. none of the above.

8. The period of the sine wave in Figure 14 given a VOLTS/DIV seting of 0.2 and a TIME/DIV setting of 5 μS, is:

   a. 29 mS.
   b. 0.00029 S.
   c. 0.029 mS.
   d. none of the above.

9. The frequency of a square wave, given a period of 50 microseconds, is closest to:

   a. 20 Hz.
   b. 400 Hz.
   c. 10,000 Hz.
   d. 20,000 Hz.

10. An ac waveform has a frequency of 2,500 Hz. Its period is closest to:

   a. 0.004 S.
   b. 40 mS.
   c. 40 μS.
   d. none of the above.

KEY TERMS

1. CALIBRATION

   The process, on a triggered oscilloscope of making certain that the vertical volts/division and horizontal time/division markings on the panel are correct.

2. CALIBRATION SIGNAL

   A square wave signal source provided on the front panel of the oscilloscope with a known peak-to-peak voltage and a known frequency and period for checking the scope calibration.

3. COUNTER

   A circuit that counts the number of pulses present in any signal fed to it.

4. FREQUENCY COUNTER

   A test instrument that measures frequency by counting the number of pulses that occur during a given time, such as one second, and presenting the data on a digital readout.

Time Constants 4

OBJECTIVES

When you finish this experiment, you will be able to:

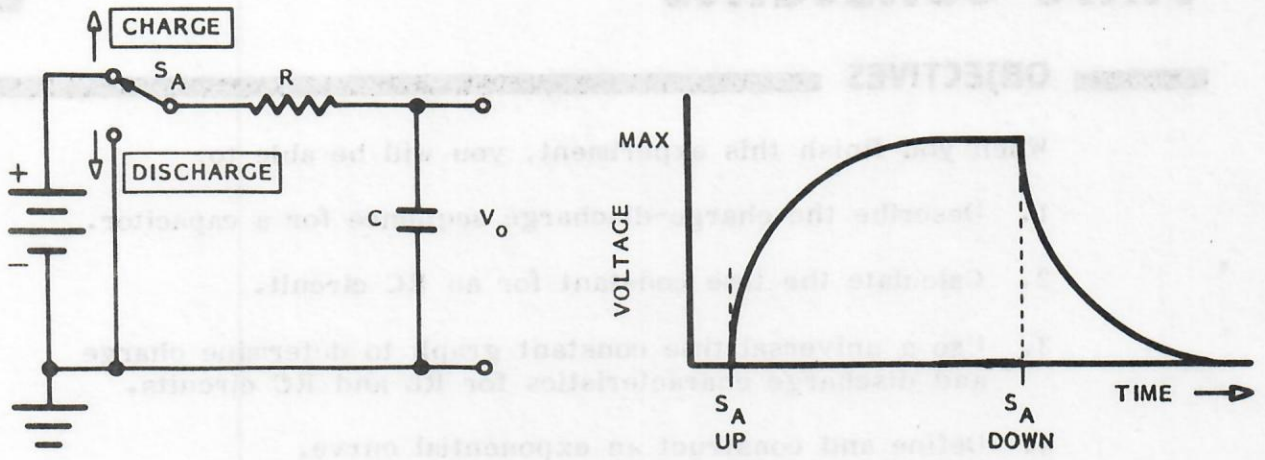
1. Describe the charge-discharge sequence for a capacitor.
2. Calculate the time constant for an RC circuit.
3. Use a universal time constant graph to determine charge and discharge characteristics for RL and RC circuits.
4. Define and construct an exponential curve.
5. Measure the voltages in an RC network and plot the charge curve on a graph.
6. Calculate the time constant for an RL circuit.
7. Observe the exponential charge-discharge curves for RL and RC circuits on an oscilloscope screen.

ADDITIONAL EQUIPMENT

a. Digital Multimeter

DESCRIPTION

When a dc voltage is applied to a capacitor, electrons accumulate on one plate of that capacitor until the full charge of Q = CV finally appears. When the full voltage appears across the capacitor, the electron flow from the voltage source stops. A specific amount of time is required to charge a capacitor to the source voltage and the time is a function of the capacitance value and the value of the resistance in series with that capacitance. If we were to plot the voltage across C in Figure 1(a) against time, it would appear as in Figure 1(b).



(a) RC CIRCUIT (b) VOLTAGE vs TIME

Figure 1 - RC circuit charge-discharge characteristics.

The larger the capacitance (C) and the larger the resistance (R) in Figure 1(a) the longer the time required to fully charge the capacitor. When the switch in Figure 1(a) is placed down, the charge on the capacitor is discharged and this too takes a specific amount of time as determined by the value of R and C. The capacitor is considered to be discharged when the net charge drops to zero volts as shown in Figure 1(b).

TIME CONSTANT

The amount of time it takes a capacitor to fully charge from the voltage source is related to the TIME CONSTANT (T). The time constant is equal to the resistance multiplied by the capacitance and is expressed as:

$$T = RC$$

where T = time constant in seconds
R = resistance in ohms
C = capacitance in farads

The time constant, T, is not the time required for a full charge; it is the time needed to charge the capacitor to 63.2% of the full source voltage. During the second time constant, the capacitor will charge 63.2% of the remaining value of voltage for a total of 86.5% of the source. The third time constant brings the charge up by 63.2% of the remaining voltage for a total 95% of the source.

In five time constants the capacitor will charge to 99% of the source voltage and is then considered to be fully charged. The capacitor voltage charge and discharge characteristics as a function of time are shown in Figure 2. The graph of Figure 2 is calibrated in percentage and time constants and is called a "Universal Time Constant Exponential Curves" for the graphical solution of time constant problems.

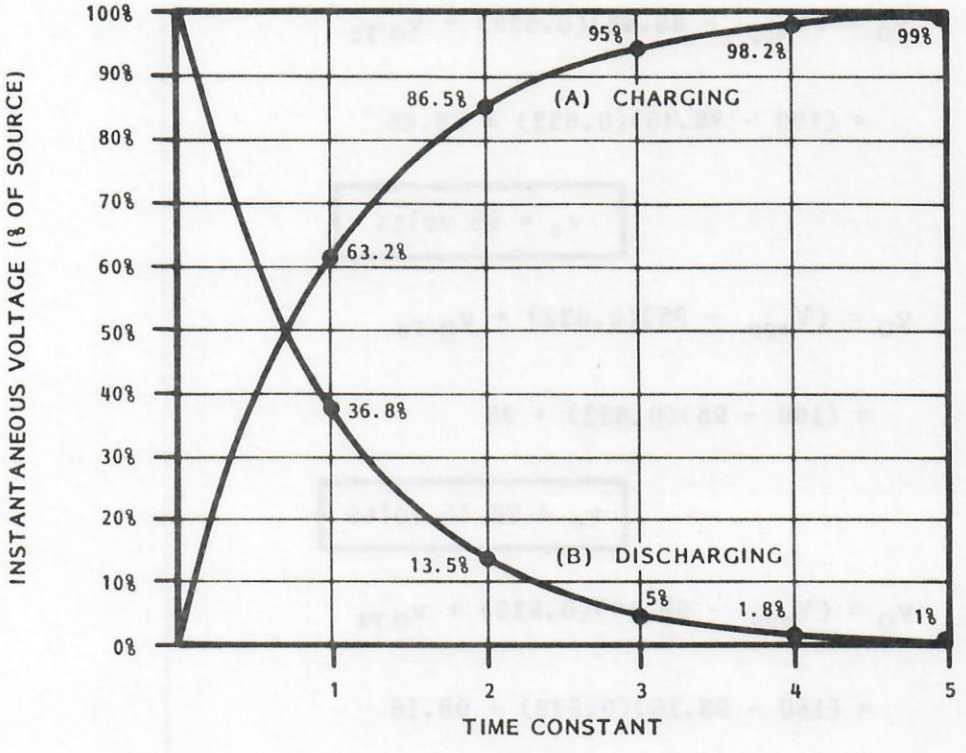


Figure 2 - Capacitor charge (A) and discharge (B) curves shown on a universal time constant graph.

The capacitor charge and discharge curves of Figure 2 are seen to be non-linear. Voltage versus time follows what is called an EXPONENTIAL CURVE. This curve results because as the voltage rises to the maximum value it will increase only 63.2% of the remaining value in each time constant (T). Thus, for curve A of Figure 2, given an applied voltages of 100 volts, we have the following output voltages at the end of each time constant:

T1 $v_O = V_{app} \times 63.2\%$

$= 100 \times 0.632$

$v_o = 63.2$ volts

T2 $v_O = (V_{app} - 63.2\ v)(0.632) + v_{O\,T1}$

$= (100 - 63.2)(0.632) + (63.2)$

$v_o = 86.46$

T3 $v_O = (V_{app} - 86.46)(0.632) + v_{O\,T2}$

$= (100 - 86.46)(0.632) + 86.46$

$v_o = 95$ volts

T4 $v_O = (V_{app} - 95)(0.632) + v_{O\,T3}$

$= (100 - 95)(0.632) + 95$

$v_o = 98.16$ volts

T5 $v_O = (V_{app} - 98.16)(0.632) + v_{O\,T4}$

$= (100 - 98.16)(0.632) + 98.16$

$v_o = 99$ volts

The discharge curve (B), shown in Figure 2, is a decreasing exponential curve. As shown, it requires one time constant (T) to discharge by 63.2% of the source voltage or to 36.8% of the full charge. By the second time constant, the voltage has dropped another 63.2% to a total of 13.5% and by the fifth time constant only 1% of the voltage remains. The capacitor is considered to be discharged after 5 time constants.

RC TIME CONSTANT CALCULATIONS

Some typical RC time constant calculations are shown below.

Given a 100 K resistor and a 100 μF capacitor, the time constant, T, is:

$$T = RC$$

$$= (100\ K)\ (100\ \mu F)$$

$$= (100 \times 10^{3})(100 \times 10^{-6})$$

$$\boxed{T = 10 \text{ seconds}}$$

Note that to convert μF to farads it is necessary to multiply by 10^{-6}. To convert pF or $\mu\mu$F to farads it is necessary to multiply by 10^{-12}. For example:

Given a resistor of 100 K and a 100 pF capacitor, the time constant, T is:

$$T = RC$$

$$= (100\ K)(100\ pF)$$

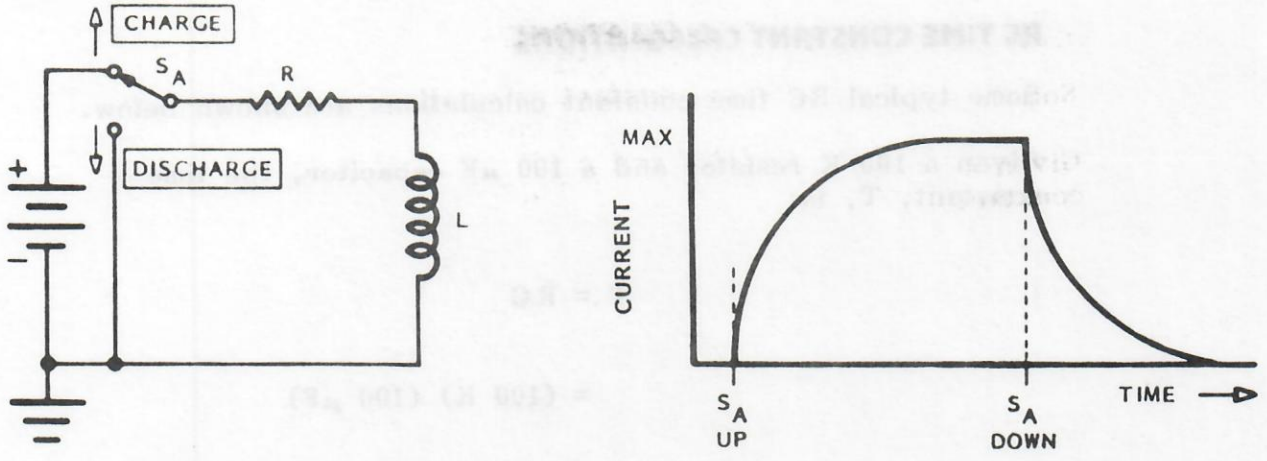
$$= (100 \times 10^{3})(100 \times 10^{-12})$$

$$\boxed{T = 10 \times 10^{-6}\ S \quad \text{or} \quad 10\ \mu S}$$

Observe that as the capacitance value is reduced, the time constant gets smaller.

INDUCTIVE TIME CONSTANT

Just as it takes a specific amount of time for a capacitor to charge to the full source voltage (5 time constants for a 99% charge) it also takes a specific amount of time for the current in an inductive circuit to rise to the full steady state value. The inductor charge-discharge circuit and the inductor's exponential curve are shown in Figure 3.



(a) RL CIRCUIT (b) CURRENT vs TIME

Figure 3 - RL circuit charge and discharge characteristics.

The inductor requires one time constant for the current to rise from zero to 63.2% of the maximum value. In five time constants the current in the inductor will reach 99% and this is considered to be at maximum. The universal time constant chart shown in Figure 4 displays the current charge and discharge curves. Note that the graph is identical to that of Figure 2 except that the Y axis is labeled as percentage of the steady state current value rather than voltage.

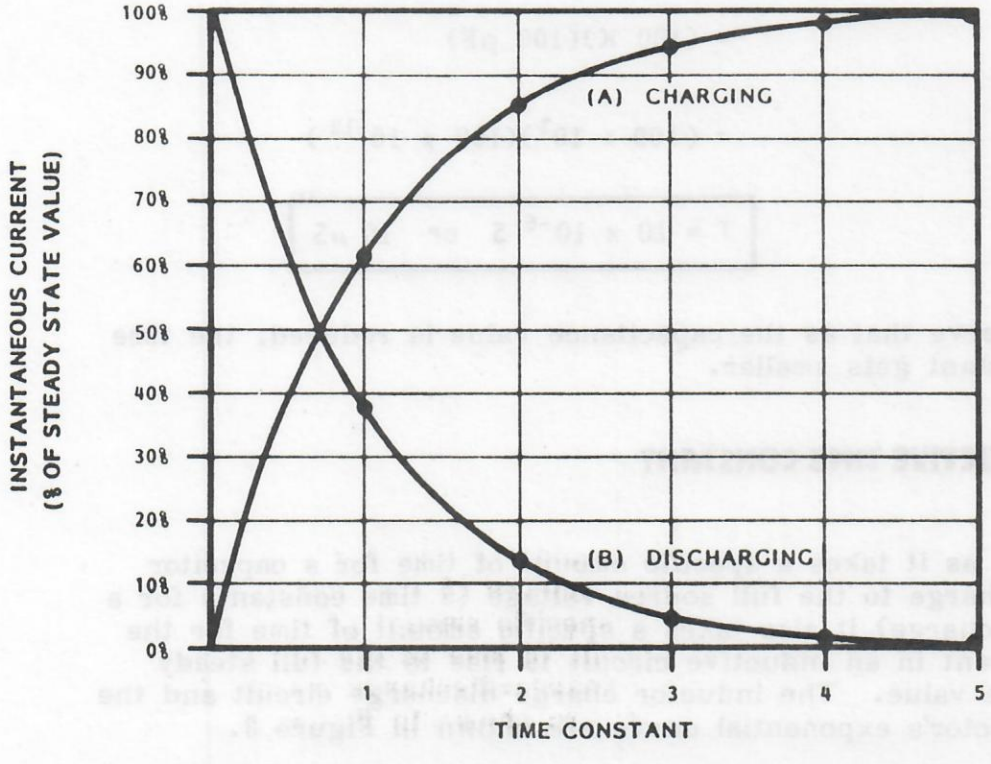


Figure 4 - Inductor charge (A) and discharge (B) current curves on the universal time constant graph.

INDUCTIVE TC CALCULATIONS

The time constant of an inductive circuit is determined from the ratio of the circuit inductance to the circuit resistance. This is expressed as

$$T = \frac{L}{R}$$

where T = time constant in seconds
L = inductance in henries
R = resistance in ohms

For example, given a series resistance of 1120 ohms and an inductance of 75 mH, the time constant is:

$$T = \frac{L}{R}$$

$$= \frac{75 \times 10^{-3}}{1120}$$

$$T = 66.9 \times 10^{-6} \text{ S or } 66.9 \mu S$$

In the procedure that follows you will measure the time constant of an RC network and plot the charge curve on a graph. You will then build a Metronome circuit as an application of the RC network. The final part of the experiment deals with RL waveshapes and time constants.

PROCEDURE

1. Wire the circuit shown in Figure 5.

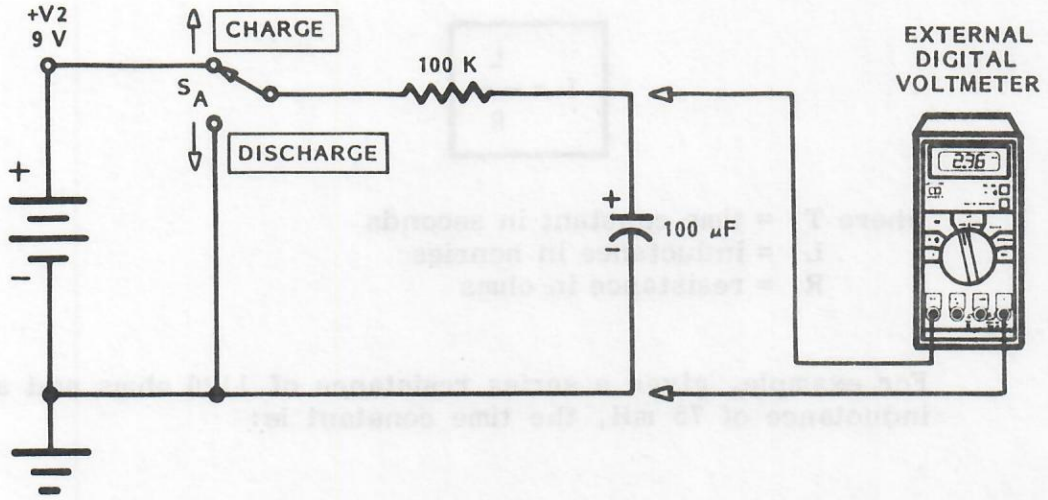


Figure 5 - RC time constant EXPERIMENT.

4.1 RC TIME CONSTANT

2. Set Switch SA DOWN.

   Set the Ed-Lab power switch to ON.

3. This part of the experiment requires two students, one to hold a watch and call out "READ" at preset time intervals and the other to read the meter at the proper time and record the voltages in Table 1.

4. Wait until the meter reads zero volts or some very low value.

5. Using the watch, student 1 will call "GO" and student 2 will set switch SA UP and be prepared to read the meter and record the voltages in Table 1. Student 1, holding the watch, will call "READ" AT 5, 10, 20, 30 etc., seconds, first at 5 and then at every 10 seconds up to 100 seconds.

TIME (S)	VOLTS
0	0
5	
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	

TABLE 1 - Capacitor voltage versus time.

6. Assuming a 9 volt source (+V2) and a 10 second time constant (as calculated earlier in the description), the projected curve is plotted in Figure 6.

Plot the points for the data gathered in Table 1 on this curve.

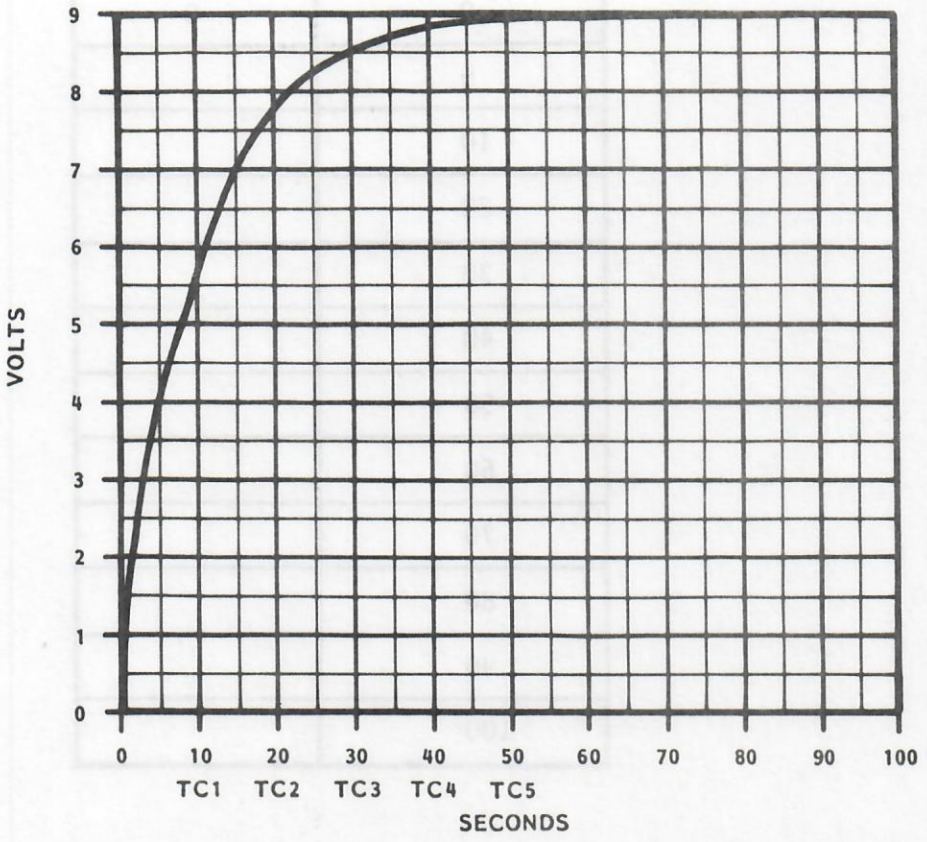


Figure 6 - Exponential curve.

How close are the plotted points to the projected exponential curve?

4.2 RC EXPONENTIAL CURVE DISPLAY

7. The exponential charge and discharge curves can be shown on an oscilloscope if a fast square wave input to the RC network is used. Wire the circuit of Figure 7 as shown.

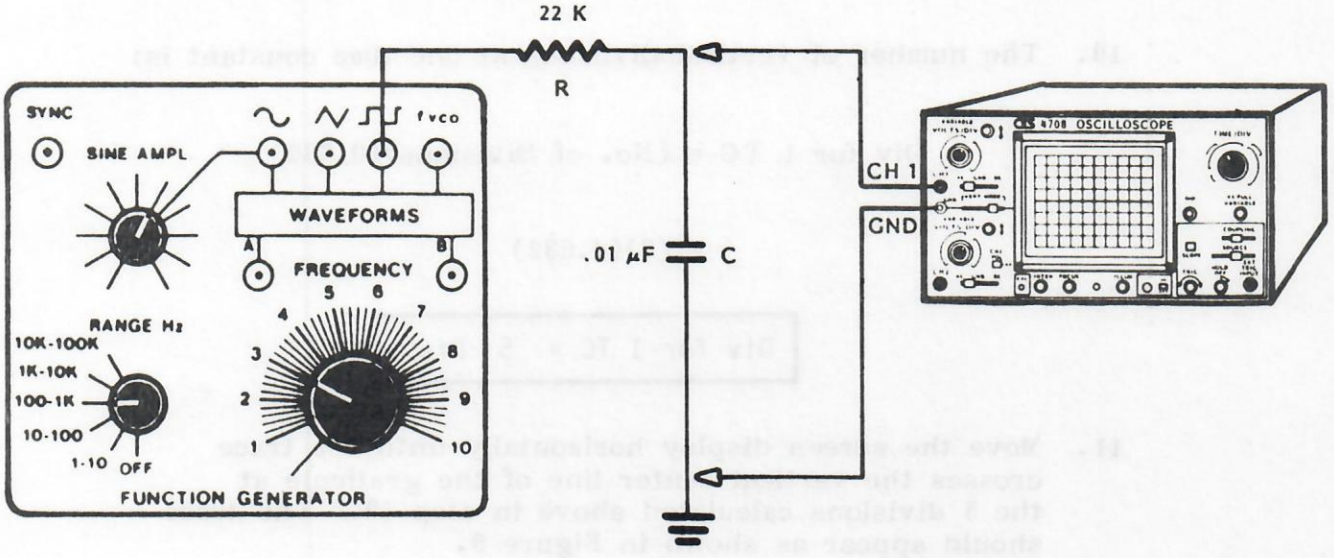


Figure 7 - RC waveform and timing EXPERIMENT.

8. Set the Function Generator for a 300 Hz square wave input.

   Set the oscilloscope controls as follows:

VERT MODE	CH 1	TIME/DIV	0.5 mS
VOLTS/DIV	0.5	SOURCE (SYNC)	CH 1
INPUT SWITCH	DC		

9. Adjust the display so that it covers the full 8 vertical divisions on the screen using the VARIABLE control. Sketch the display in Figure 8.

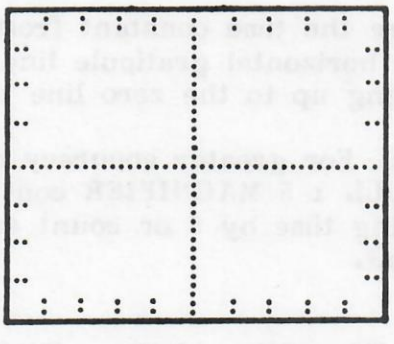


Figure 8 - Charge-discharge waveform for the capacitor in the circuit of Figure 7; EXPERIMENT.

10. The number of vertical divisions at one time constant is:

Div for 1 TC = (No. of Divisions)(0.632)

= (8)(0.632)

Div for 1 TC = 5 Div

11. Move the screen display horizontally until the trace crosses the vertical center line of the graticule at the 5 divisions calculated above in step 10. The trace should appear as shown in Figure 9.

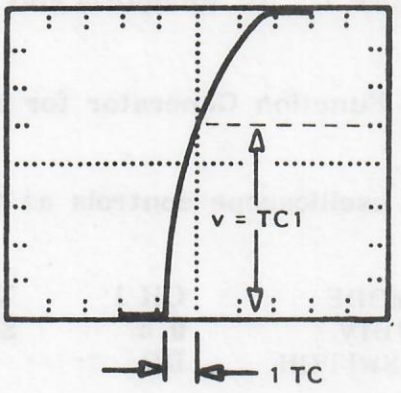


Figure 9 - Positioning of the exponential curve to measure the time constant; EXPERIMENT

12. Measure the time constant from the markings on the center horizontal graticule line. (Move trace centering up to the zero line to make the reading simpler.)

NOTE: For greater accuracy of measurement you may use the PULL x 5 MAGNIFIER control. Be sure to divide the resulting time by 5 or count each minor division as 0.02 mS.

TC = (No. of Minor Divisions)(0.1 mS)

= ( )(0.1)

MEASURED TIME CONSTANT	T = _____ mS

13. The theoretical time constant for R = 22 K and C = 0.01 μF is:

$$T = R\ C$$

$$= (22 \times 10^{3})(0.01 \times 10^{-6})$$

THEORETICAL TIME CONSTANT	T = _____ mS

How close in value are the measured and theoretical time constants for the circuit of Figure 7?

_____

4.3 METRONOME CIRCUIT (OPTIONAL)

14. The series RC network is useful in many circuits where timing is required. The circuit of Figure 10 uses the RC network time constant to act as a timing circuit for the beeps heard from the loudspeaker of the Metronome. The Unijunction Transistor (UJT, Q10) is discussed in a later experiment.

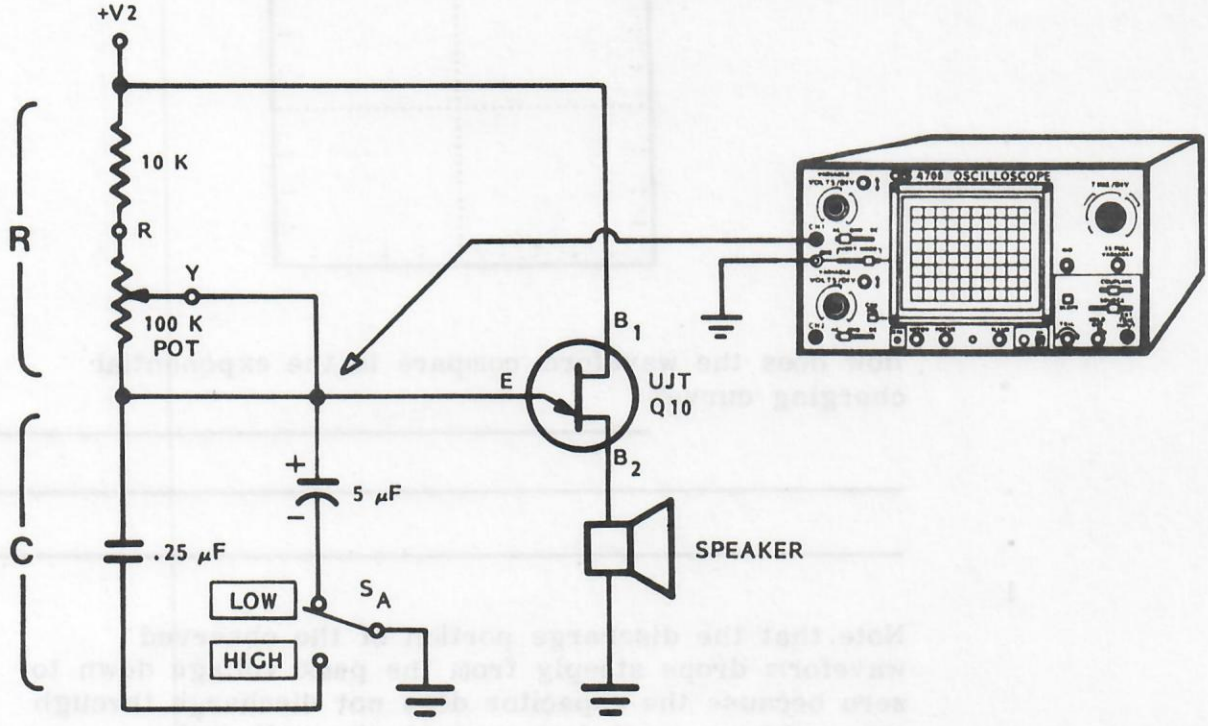


Figure 10 - METRONOME circuit; EXPERIMENT.

The resistance, R, in Figure 10 is the series combination of the 10 K and variable 100 K pot. The capacitor, C, is either the 0.25 μF or the 5 μF as selected by switch SA.

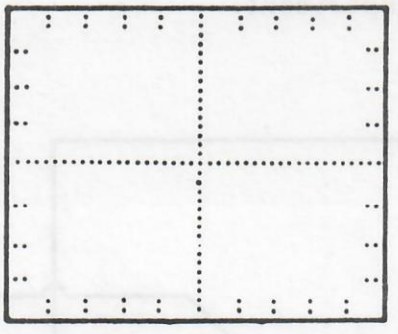
Wire the circuit in Figure 10.

15. Place Switch SA UP and DOWN and vary the 100 K pot. Describe the effects.

16. Set Switch SA DOWN (0.25 μF capacitor for highest frequency) and adjust the 100 K pot (CW) for the highest frequency.

Adjust the oscilloscope to observe two or three cycles of the waveform generated across the capacitor.

Sketch two cycles of the waveform observed.



How does the waveform compare to the exponential charging curve?

Note that the discharge portion of the observed waveform drops steeply from the peak voltage down to zero because the capacitor does not discharge through the resistance path but through the unijunction transistor instead and thus has a very low resistance discharge path resulting in a very short time constant.

4.4 RL OSCILLOSCOPE DISPLAY (OPTIONAL)

17. The exponential charge and discharge current curves for an inductor can also be viewed on an oscilloscope screen.

    Wire the circuit of Figure 11. Note that the 50 mH and 25 mH are wired in series resulting in a greater and thus more easily measured time constant.

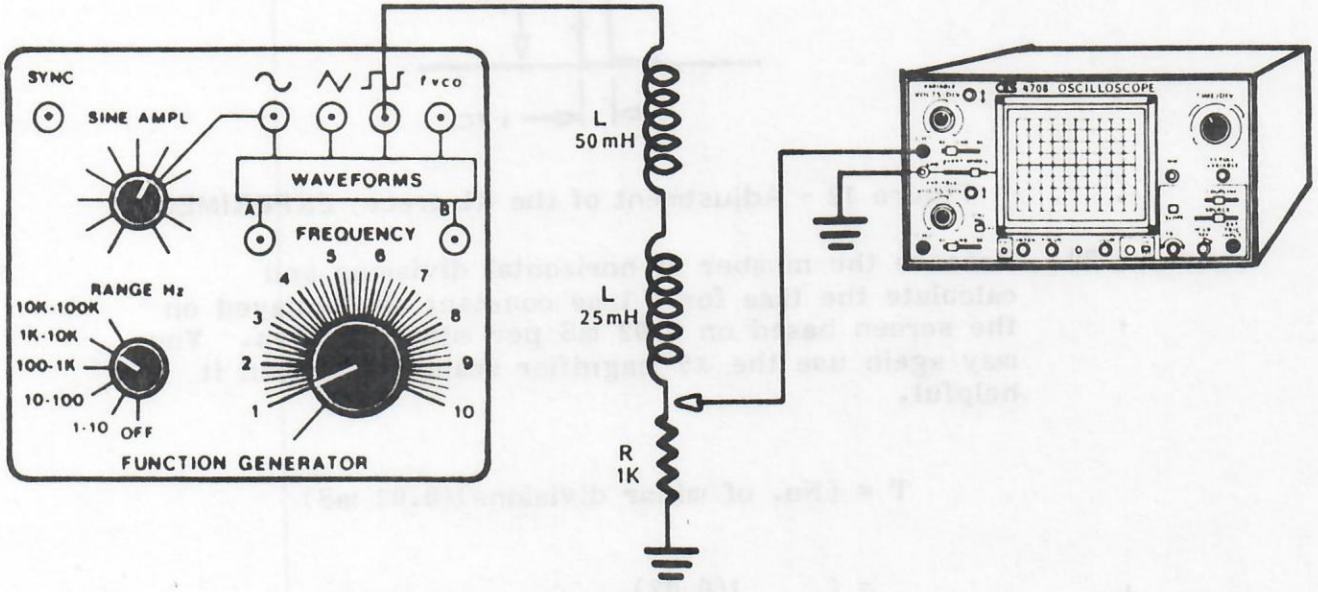


Figure 11 - RL waveform and timing EXPERIMENT.

18. Set the oscilloscope controls as follows:

V/DIV	0.2	VERT MODE	CH 1
TIME/DIV	0.1 mS	INPUT SW	DC
SOURCE (SYNC)	CH 1		

19. Adjust the display so that it covers exactly 8 boxes vertically using the VARIABLE control. The voltage at 1 time constant will be 5 boxes (8 boxes times 0.632).

    Using the horizontal centering control, position the rise portion of the trace so that it crosses the center vertical line of the graticule at a height of 5 divisions as shown in Figure 12.

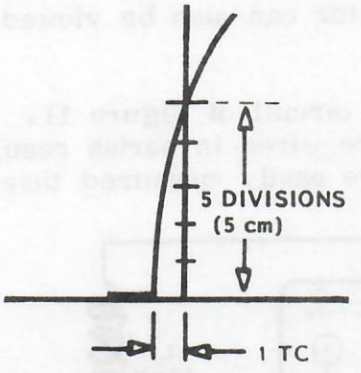


Figure 12 - Adjustment of the RL trace; EXPERIMENT.

20. Measure the number of horizontal divisions and calculate the time for 1 time constant as displayed on the screen based on 0.02 mS per minor division. You may again use the x5 magnifier scale if you find it helpful.

$$T = (\text{No. of minor divisions})(0.02\ \text{mS})$$

$$= (\quad\quad)(0.02)$$

MEASURED	T = _____ mS

21. Calculate the theoretical time constant for L = 0.075 H (75 mH) and for R = 1120 ohms. Note that R equals inductor's resistance which is 120 ohms and the 100 ohm generator resistance for a total of R = 1220 ohms.

$$T = \frac{L}{R}$$

$$= \frac{0.075}{1220}$$

THEORETICAL	T = _____ mS

Compare the theoretical and measured time constants. Are they close?

_____

Account for any differences.

CONCLUSIONS

We have learned from this experiment that:

The charge and discharge curves for a capacitor and inductor are exponential.

The capacitor exponential curve is plotted in voltage versus time.

The inductor exponential curve is plotted in current versus time.

The time constant of an RC circuit is equal to

$$T = R\ C$$

A capacitor charges to 63.2% of the source voltage in the first time constant.

A capacitor increases its charge by 63.2% of the remaining source voltage each additional time constant.

A capacitor requires 5 time constants to charge to 99% of the source voltage.

The time constant of an RL circuit is equal to:

$$T = \frac{L}{R}$$

An inductor current flow reaches 63.2% of its steady state current in one time constant.

The inductor current increase by 63.2% of the remaining steady state value each additional time constant.

An inductor requires 5 time constants to reach 99% of the steady state current.

The exponential charge and discharge curves can be displayed on an oscilloscope screen.

ASSIGNMENT

Answer the following True-False questions.

1. The larger the capacitance value in an RC circuit the longer the time constant. ____

2. As the value of the series resistor in the RC network is increased the time constant gets longer. ____

3. The time constant for an RC circuit is calculated from ____

$$T = \frac{R}{C}$$

4. The time constant for an RC circuit is that time required to charge the capacitor from 0 volts to 100% of the source. ____

5. A capacitor charges at an exponential rate but discharges at a linear rate. ____

6. If a capacitor is connected across a 100 volt source, the level of charge at the end of the second time constant will be approximately 86.5 volts. ____

7. An RC network composed of a 22 K resistor and 0.22 μF capacitor has a time constant of 4.84 mS. ____

8. A capacitor is considered to be fully charged after one time constant. ____

9. An RC network composed of a 470 K resistor and an 800 pF capacitor has a time constant of 376 mS. ____

10. The time constant of an RL circuit is calculated from ____

$$T = L\ R$$

11. An RL circuit consists of a 2 K resistor in series with a 3 H inductor. This produces a time constant of 1.5 mS. ____

12. An oscilloscope screen display of an exponential curve has an amplitude of 6 divisions. The first time constant occurs at a vertical amplitude of 4.5 divisions. ____

KEY TERMS

1. METRONOME

   A clocklike device that can be adjusted to tick at different speeds. Used to help musical students keep time.

2. TIME CONSTANT

   The time required for an exponential quantity to change 63.2% of the total voltage or current. In an RL circuit, it is the time required for the current to rise to 63.2% of the maximum current. In an RC circuit, it is the time required to charge a capacitor to 63.2% of the maximum voltage.

3. UJT

   Unijunction Transistor, also called a double base diode. It can be used in conjunction with an RC network to form an electronic equivalent of the mechanical metronome.

BH Magnetization Curve 5

OBJECTIVES

When you finish this experiment, you will be able to:

1. Set up and operate the oscilloscope in the X-Y mode for a graphic plot.
2. Wire and test a circuit that will display the BH response of a transformer.
3. Explain the operation of the BH display circuit.
4. Label and explain the significant points on a BH curve.
5. Define what is meant by a core saturation and retentivity.
6. Define the term Hysteresis Loop.

ADDITIONAL EQUIPMENT REQUIRED

a. Transformer Module Card, CES 306.

DESCRIPTION

In the air core coil shown in Figure 1(a), the field intensity (H) can be increased by increasing the current flow. There is a corresponding increase in the flux density (B) in the core area of the inductor. As shown by the graph of Figure 1(b), the relationship between B and H is linear and B does not increase at a very rapid rate. We know, from an earlier information sheet that

$$B = \mu H$$

and that for air, μ equals 1. Thus, for an air core coil, B is equal to H and H is equal to AT (Ampere Turns).

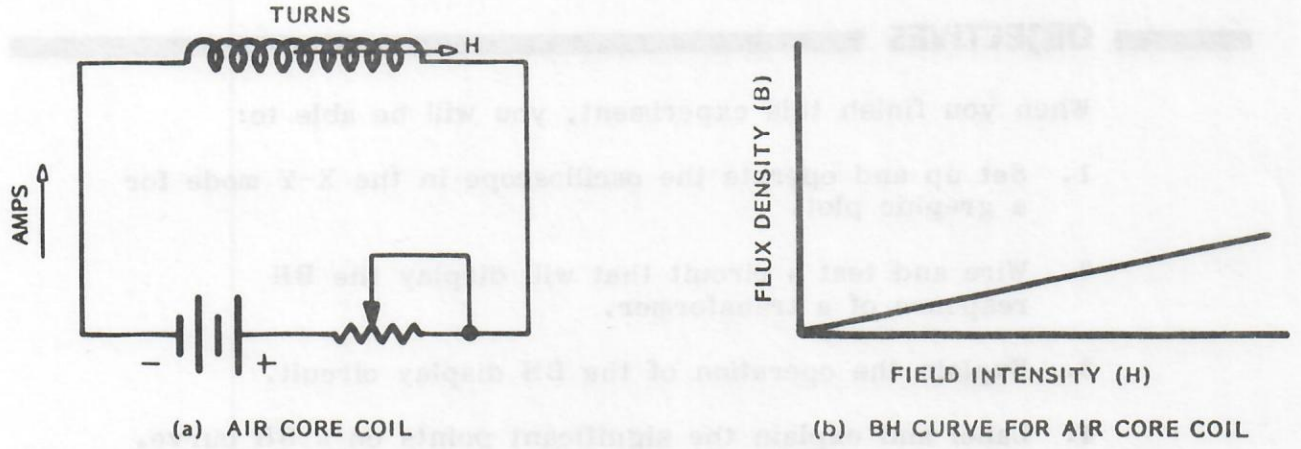


Figure 1 - Air core coil and its BH curve.

IRON CORE INDUCTOR

Adding an iron core to an air core coil, as in Figure 2(a), increases the flux(θ) and flux density (B) drastically since, as noted, B is equal to μH. If the μ of the core added in Figure 2(a) is as little as 50, then B has been increased by 50 times. While this is very desirable, the increase in B is also accompanied by saturation and non-linearity as shown in the BH curve of Figure 2(b).

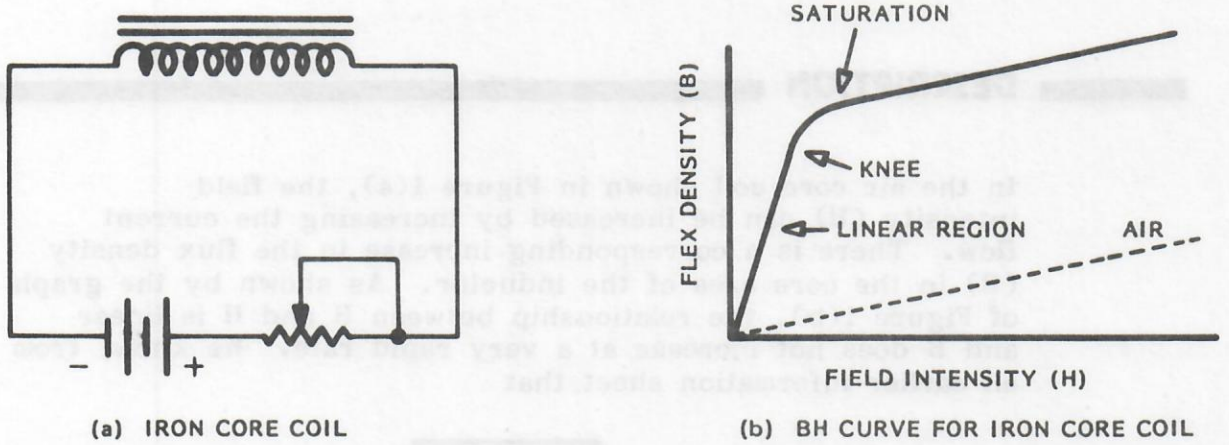


Figure 2 - Iron core coil and its BH curve.

The non-linear BH curve for the iron core coil, shown in Figure 2(b), can be divided into three areas as marked. The flux density rises at a linear rate until the KNEE at which point the flux density increases very slowly for increases in H because almost all of the dipoles are now aligned. For values of H beyond the knee, there is Saturation.

SATURATION

The reason for the non-linear BH curve is the alignment of the magnetic dipoles in the core material. (The magnetic dipole theory was explained earlier in Unit F, Information Sheet 1.) As the field intensity increases, more and more of the magnetic dipoles in the core fall into alignment to increase the total flux. Eventually, as H is increased, almost all the dipoles are aligned and further increases in H do not produce a great increase in B thus producing the knee in Figure 2(b).

When all the dipoles are aligned, further increases in H produce increases in B that are the same as would occur with an air core coil. The core can no longer make any contribution to B because all of its dipoles now have been aligned. This conditon is known as SATURATION.

RETENTIVITY AND COERCIVITY

While the BH curve of Figure 2(b) represents the manner in which the flux density increases with H, it does not represent the way in which the flux density changes with a decrease in H. As H is decreased by reducing the current through the coil, the decrease in B does not correspond to the rate of increase because of RETENTIVITY as described on the next page. The return plot for B-H is shown in Figure 3, from B to C to D.

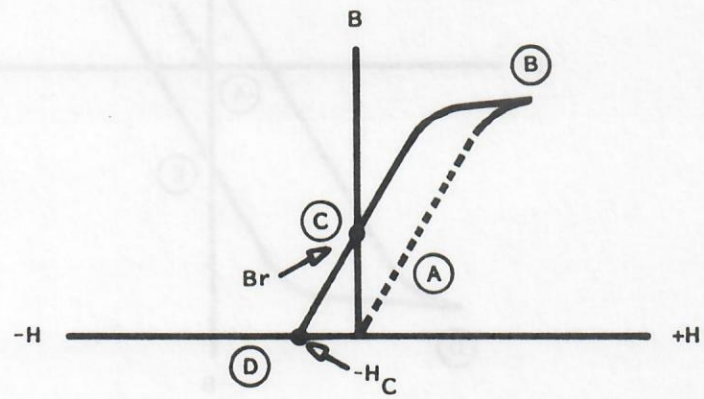


Figure 3 - BH curve created by reducing H.

Retentivity, B_r, is the following: When the magnetizing force is removed, not all the dipoles in the core material return to their original scattered positions. As a result, as shown in Figure 3, when the current through the coil is brought down to zero (point C), the flux density does not drop to zero but RETAINS some flux, B_r. In order to demagnetize the core, the direction of the flow of current must be reversed to some negative value, -H. This intensity of -H is defined as the COERCIVITY (H_c), and point D of the BH curve in Figure 3, where the flux density drops to zero, is labeled $-H_c$.

HYSTERESIS CURVE

The BH curve shown earlier in Figure 3 illustrates the manner in which the flux density of an unmagnetized iron core responds as H is increased and then decreased. If an alternating current is applied to the inductor, the BH curve developed is that shown in Figure 4 in a four quadrant plot.

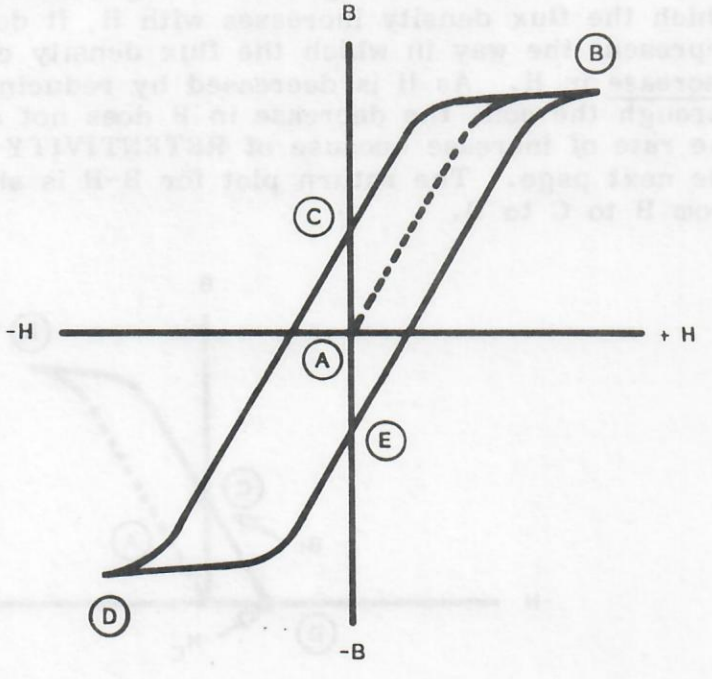


Figure 4 - Typical hysteresis curve of an iron core

The word, HYSTERESIS, means lag or delay due, in this case, to the inertia of the magnetic dipoles in aligning and then realigning again. The hysteresis curve shown in Figure 4 starts initially at point A with no current flow and no flux density. The dotted line shows the initial rise from A to B, saturation. As the current is reduced to zero, the flux density returns to point C and, as the current reverses, the curve goes into saturation again at point D.

The current reduces to zero again and then goes positive to produce the flux density curve from D to E and up to point B. The configuration formed by these points is known as the HYSTERESIS LOOP or HYSTERESIS CURVE.

The concept of the hysteresis loop or curve is important because in order for a transformer to transfer energy from the primary to secondary, changes in primary current must result in flux changes. If there is too much current, the transformer is operated in the saturation area and there will be little or no flux change and so no transfer of energy from primary to secondary. This results in distortion of the signal that appears across secondary winding.

It is possible to wire a transformer into a test circuit that will display the Hysteresis Loop on an oscilloscope screen as will be done in this experiment.

X-Y OSCILLOSCOPE OPERATION

In order to display the BH curve of a transformer on the oscilloscope screen, it is necessary to plot a response based on two voltages, one voltage representing B and the other representing H. The X-Y operation of the oscilloscope is shown in Figure 5 where the signal voltage representing H is fed to the horizontal input and the signal voltage for B is fed to the vertical input.

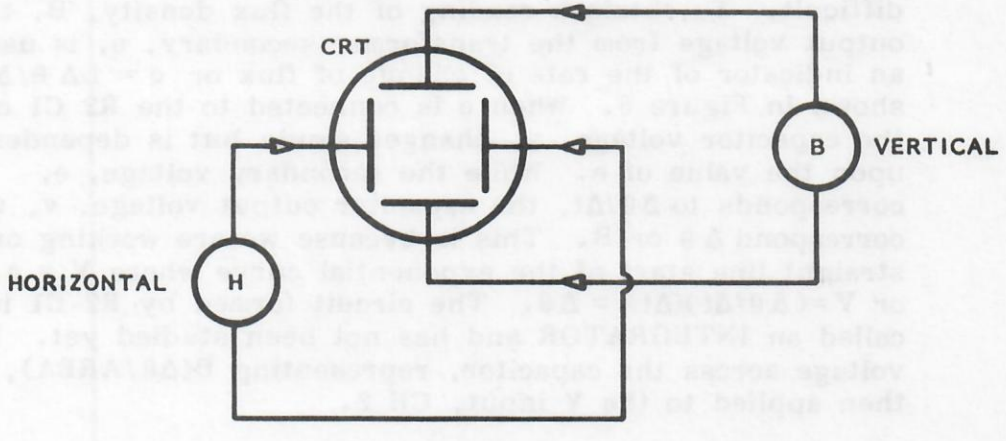


Figure 5 - Basic BH display set-up for the oscilloscope.

To switch the oscilloscope to its X-Y function, rotate the TIME/DIV switch to the X-Y position (CCW). For most dual trace scopes, the CH 1 input is the X axis and the CH 2 input is the Y axis.

BH CURVE PLOT

The BH curve can be plotted in the X-Y mode of the oscilloscope using the circuit shown below in Figure 6.

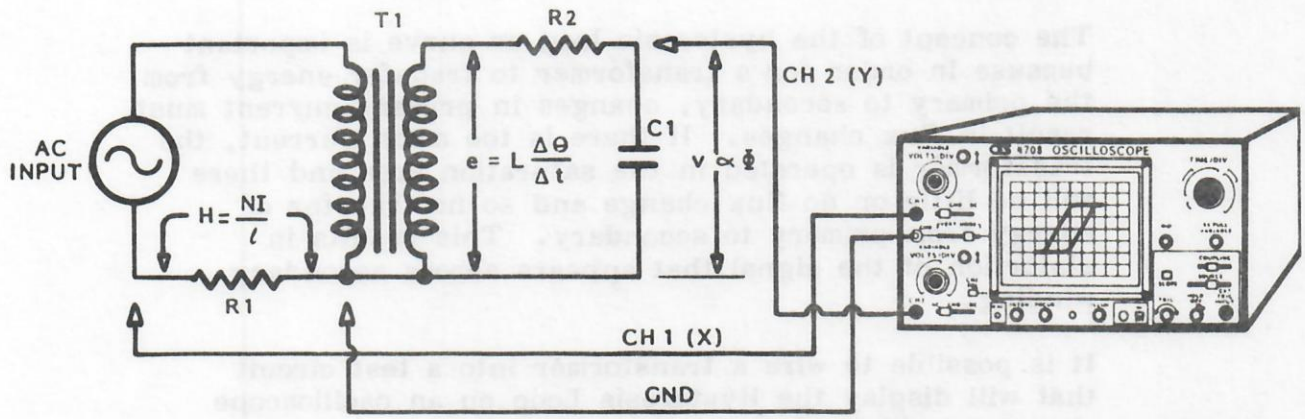


Figure 6 - Test set-up to display the BH curve for T1.

The ac input voltage provides a varying current (I) and thus a varying magnetic field intensity (H). Because the number of turns and the path length of the core (ℓ) are constant, the intensity (H) varies directly as the current which varies as the voltage across R1. The voltage drop across the small resistance of R1, 2.5 ohms, is used for a plot of H and is fed to the X axis amplifier, CH 1.

Describing the voltage corresponding to B is a bit more difficult. To obtain a reading of the flux density, B, the output voltage from the transformer secondary, e, is used as an indicator of the rate of change of flux or $e = L\Delta\theta/\Delta t$ as shown in Figure 6. When e is connected to the R2 C1 circuit, the capacitor voltage, v, changes slowly but is dependent upon the value of e. While the secondary voltage, e, corresponds to $\Delta\theta/\Delta t$, the capacitor output voltage, v, will correspond $\Delta\theta$ or B. This is because we are working on the straight line start of the exponential curve where $V = e\Delta t$ or $V = (\Delta\theta/\Delta t)(\Delta t) = \Delta\theta$. The circuit formed by R2 C1 is called an INTEGRATOR and has not been studied yet. This voltage across the capacitor, representing B($\Delta\theta$/AREA), is then applied to the Y input, CH 2.

In the procedure that follows, you will test the X-Y function of the oscilloscope and then display the Hysteresis Loop of one of the transformers mounted on the CES 306 Transformer Module.

PROCEDURE

1. Wire the circuit shown in Figure 7.

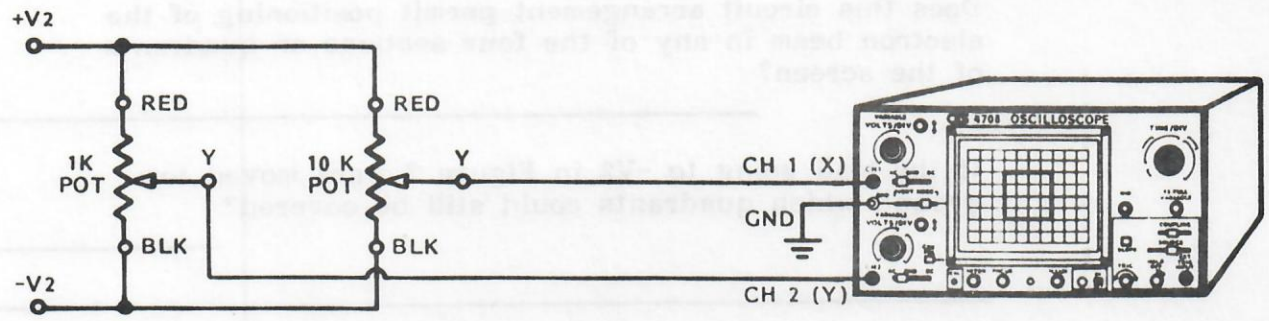


Figure 7 - X-Y oscilloscope operation EXPERIMENT.

> CAUTION - Use the minimum amount of brightness, just enough to permit you to view the spot on the screen. Excessive intensity could burn the screen coating if the beam is allowed to remain in one spot too long and too bright.

5.1 X-Y SCOPE OPERATION

2. Set up the oscilloscope controls as follows:

CH 1 and CH 2 V/DIV	5
CH 1 and CH 2 INPUT SWITCH	GND
TIME/DIV	X-Y

Set the 1 K and 10 K pots on the trainer to the center of their rotation.

3. Apply power to the Ed-Lab trainer and the oscilloscope and center the dot on the screen using X POSITION CONTROL and the Y POSITION CONTROL.

4. Place both the CH 1 and CH 2 INPUT switches in the DC position.

The display will be a bright dot located somewhere within the center of the screen area outlined in Figure 7.

5. Using the 1 K and 10 K pots, move the beam into various sections or quadrants of the screen.

   Does this circuit arrangement permit positioning of the electron beam in any of the four sections or quadrants of the screen?

   _____

   If the lead going to -V2 in Figure 7 were moved to ground which quadrants could still be covered?

   _____

   _____

5.2 HYSTERESIS CURVE DISPLAY

6. Remove the existing wiring and assemble the circuit shown in Figure 8.

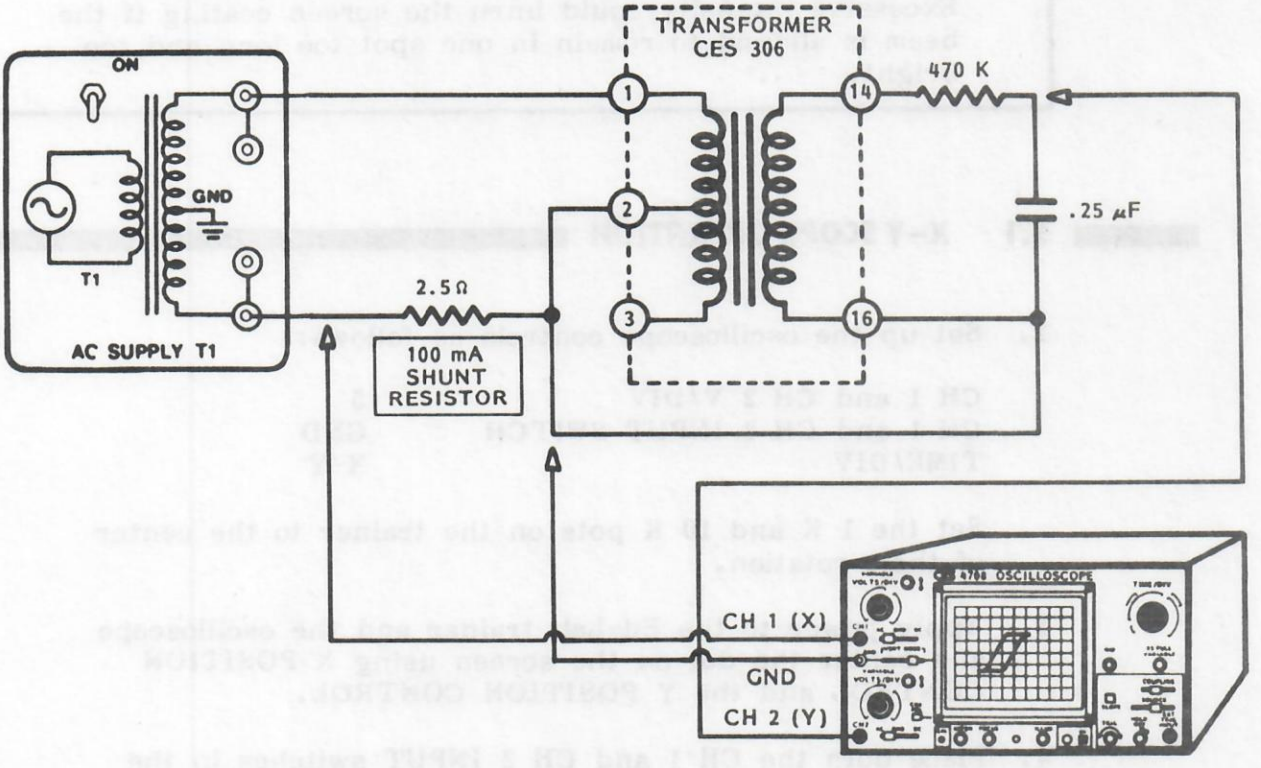


Figure 8 - Wiring for hysteresis curve display; EXPERIMENT.

7. Plug the CES 306 Transformer Module into the PC socket with pin 1 in the upper left corner.

8. Set the oscilloscope controls as follows

CH 1 V/DIV	0.2	CH 1 and CH 2 INPUT SW	DC
CH 2 V/DIV	2	TIME/DIV	X-Y

9. Apply power and center the trace as follows:

   a. Set CH 1 INPUT switch to GND

   b. Adjust the vertical line so that it is exactly centered, using the X POSITION control

   Return the CH 1 INPUT switch to the DC position.

   c. Set the CH 2 INPUT switch to GND.

   d. Adjust the horizontal line so that it is exactly centered, using the CH 2 Y POSITION control.

   Return the CH 2 INPUT switch to the DC position.

   The hysteresis loop will now appear on the crt properly centered.

10. Draw the hysteresis loop shown on the screen in Figure 9.

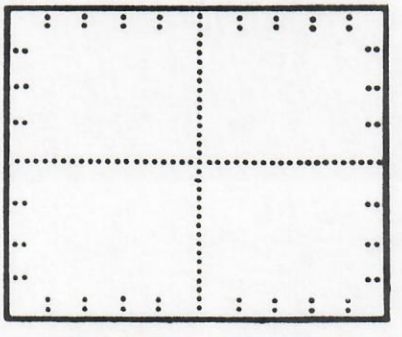


Figure 9 - Hysteresis loop displayed on the screen.

Is the hysteresis loop shown on the oscilloscope screen the same as the theoretical plot shown earlier in Figure 4?

CONCLUSIONS

We have learned from this experiment that:

In an air core coil B is equal to H and their relationship is linear.

The addition of an iron core to an air core coil produces a large increase in B but destroys the linear relationship between B and H.

The BH relationship is normally presented graphically.

The BH curve illustrates the effects of core saturation and core retentivity.

The BH display of an iron core transformer shows the effects of hysteresis due to core retentivity and the lag in the dipole realignment when subjected to ac fields.

Iron core transformers suffer a delay or lag when remagnetizing their core as the ac changes polarity.

The delay of a core in changing its magnetic alignment is called hysteresis and is displayed on an X-Y plot.

An oscilloscope can be operated in the X-Y mode to show the graphic plot of two voltages.

ASSIGNMENT

Answer the following True-False questions.

1. In an air core coil B is equal to H until saturation occurs. ____

2. The addition of an iron core to an air core coil destroys the linear relationship between B and H. ____

3. In an iron core inductor, as H is increased B increases linearly up to the point called the "knee," at which point the level of B starts to flatten out. ____

4. When saturation is reached on the BH curve any increase in H produces no increase at all in B. ____

5. The reason that a core saturates is that all the magnetic dipoles have been thrown into disarray, are all mixed up and can no longer handle lines of flux. ____

6. The BH curve produced by a rising current will be the same as the BH curve produced by a decreasing current due to retentivity. ____

7. In X-Y operation of an oscilloscope one voltage is fed to CH 1, the second voltage is fed to CH 2 and the display is an X-Y plot of the two voltages. ____

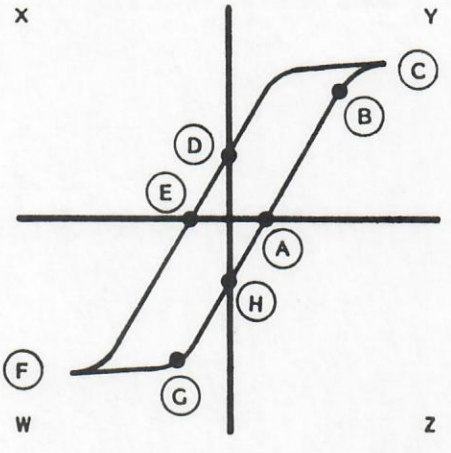


Figure 10 above refers to questions 8 and 9.

8. The display of Figure 10 is a Hysteresis curve. ____

9. Match the lettered points of Figure 10 with each of the terms listed below. (There may be more than one answer for some terms.)

a. Positive Saturation	____	f. $+H_C$	____
b. Negative Saturation	____	g. Quadrant I	____
c. Knee	____	h. Quadrant II	____
d. Linear Area	____	i. Quadrant III	____
e. $-H_C$	____	j. Quadrant IV	____

KEY TERMS

1. B

   Symbol for Flux Density, the number of magnetic lines of flux for a given cross sectional area of the magnet core.

2. BH CURVE

   Plot of magnetic flux density, B, versus the field intensity, H.

3. COERCIVITY

   The reverse current required to reduce the magnetic core flux density to zero.

4. CORE SATURATION

   The maximum flux density, beyond which the magnetic core can carry no more flux lines.

5. H

   Magnetic field intensity developed by an inductor and is equal to the ampere turns divided by the length of the coil core or $H = NI/\ell$.

6. HYSTERESIS LOOP or CURVE

   A plot of how much the magnetization of an inductor or transformer core lags the magnetizing force due to the friction of the magnetic dipoles.

7. RETENTIVITY

   A measure of how much magnetic strength remains in a material after the magnetizing force has been withdrawn.

8. X-Y OSCILLOSCOPE OPERATION

   An oscilloscope control setting that allows the screen display of the relationship between two variables, neither of which is time. In this experiment, the two variables have been B and H.

External Test Equipment 6

OBJECTIVES

When you finish this experiment you will be able to:

1. Use an external FET Multimeter and an external Audio Generator or Function Generator to conduct tests or experiments.
2. State why one side of the power lines are grounded when they enter a building.
3. List the wire colors for hot, neutral and ground leads in house wiring.
4. Identify the hot, neutral and ground leads of a duplex outlet.
5. Explain why grounding an instrument case can prevent a fatal shock.
6. Explain how a ground loop can be broken using a 3 prong to 2 prong power plug adapter and the safety hazard this creates.
7. Measure voltage in complex circuits, observing the effects of ground loops and use techniques to avoid the introduction of errors.
8. Measure the source resistance of an Audio Generator.
9. Use an Oscilloscope in the dual trace "subtract" or "invert and add" mode to measure ac voltages.

ADDITIONAL EQUIPMENT REQUIRED

a. FET (Transistor) Multimeter (CES 4007 or equivalent).
b. Function Generator (CES 4002 or equivalent).

DESCRIPTION

The Ed-Lab 651 Electricity-Electronics Trainer contains the electrical and electronic components plus various test instruments that have been used in the previous experiments. Included are dc Power Supplies, an ac Power Source, a calibrated Function Generator and an Analog Meter for dc and

ac voltages and dc current. These test instruments are included on the trainer panel for convenience. In the earlier trainer model, the Ed-Lab 650, the Function Generator was not calibrated and the Analog Meter did not have ac voltage ranges nor dc current ranges.

In practical industrial applications, the test instruments used are not mounted on trainers; they are separate units. The purpose of this experiment is to familiarize you with these instruments and some of the problems encountered when using them. A typical array of test instruments that might be found at a test-bench is shown in Figure 1.

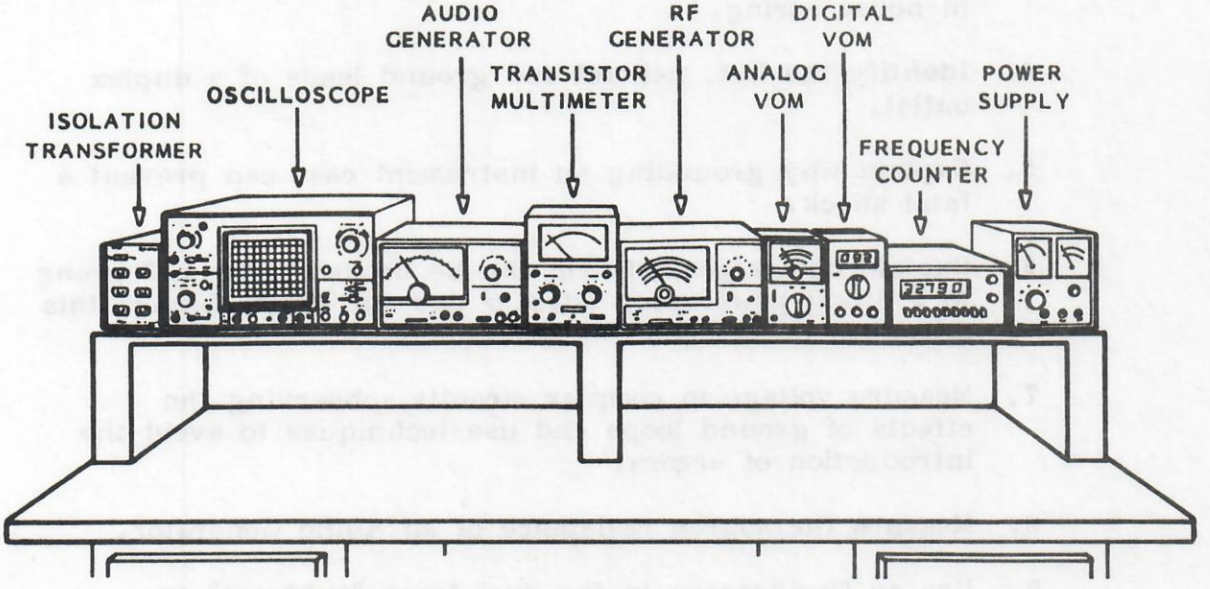


Figure 1 - Typical test instruments found at a test bench.

In the previous experiments, you have used the ANALOG VOM (Volt-Ohm-Milliammeter), the DIGITAL MULTIMETER and the OSCILLOSCOPE. These instruments may have been manufactured by one of any manufacturers such as:

BALLATINE	LEADER
B & K PRECISION	SENCORE
FLUKE	SIMPSON
GOULD	TEKTRONIX
HEWLETT-PACKARD	WAVETEK
HITACHI	and others.

In this experiment you will use the external Audio Generator (also called a Sine-Square Wave Generator or Function Generator) and the Transistor or FET Multimeter. The audio

generator, typically, may have a frequency range of 20 to 200 kHz. The external FET Multimeter you will use has a high input resistance and so does not "load down" any of the circuits under test. The Ed-Lab panel meter and most normal analog VOMs have an input resistance of 20,000 ohms per volt or an input resistance of 200,000 ohms when used on the 10 volt dc scale. The Ed-Lab panel meter has a high resistance input on the 5 volt ac range. A major problem encountered in testing that we will consider in this experiment, is the GROUNDING of the test instruments. Grounding is done for safety purposes but can also result in false instrument readings or loading when there are multiple grounds in the system. Grounding systems are explained below to enable you to understand the reasons grounds are used and how they might affect test readings.

GROUNDING SYSTEMS

All electrical power distribution systems to homes and industrial sites have one terminal of the power line connected to earth ground. The reason for grounding one side of the power line is to minimize the possibility of voltage surges or sudden increases due to lightning striking the power lines. It is hoped that the surge caused by a lightning strike will flow to ground rather than enter the building. The electrical arrangement from the power company's local transformer (also discussed in "Concepts of AC", Information Sheet 1, Part G1, Figure 2) is shown in Figure 2.

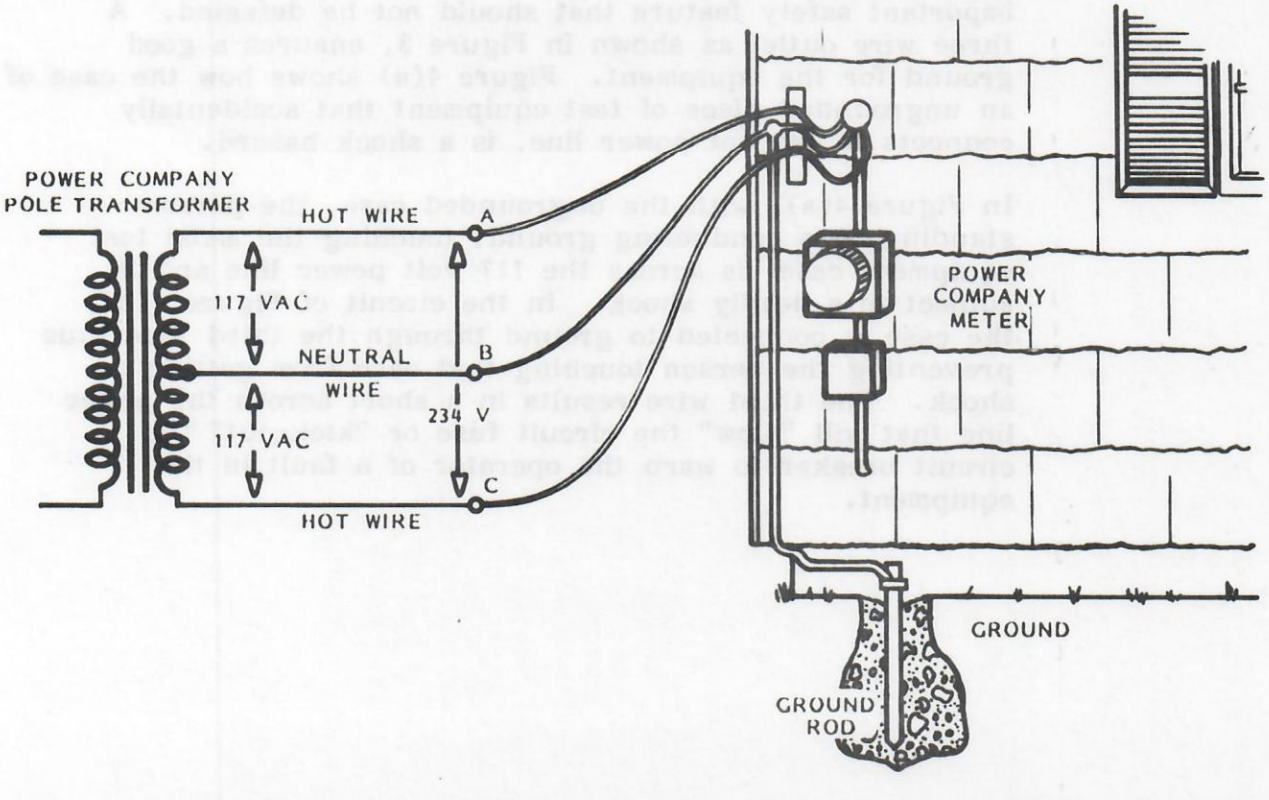


Figure 2 - Grounding of the neutral wire at entrance to house.

Note that the NEUTRAL wire is connected to earth ground just as the power lines enter the house. The power is distributed through the house using suitable conductors which connect to outlets in a very specific manner as shown in Figure 3.

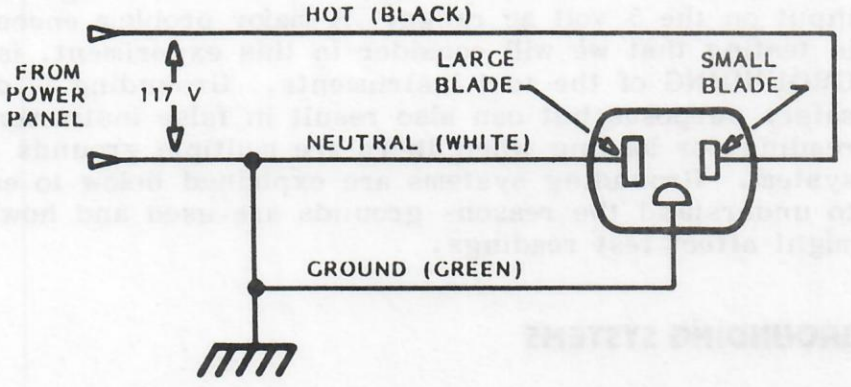
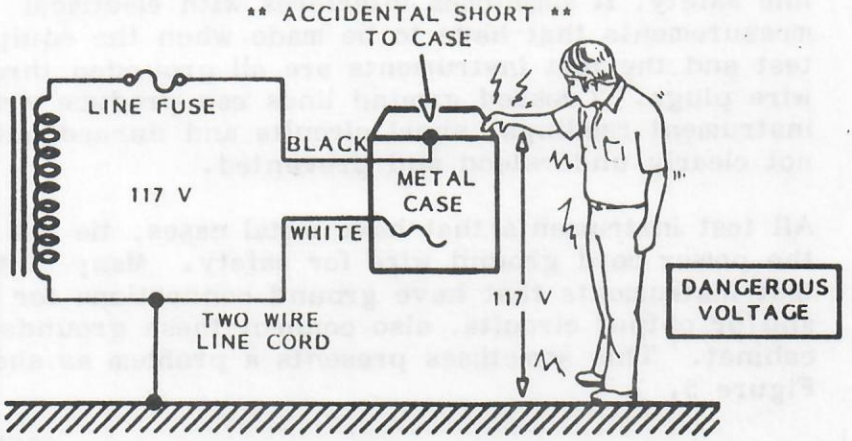


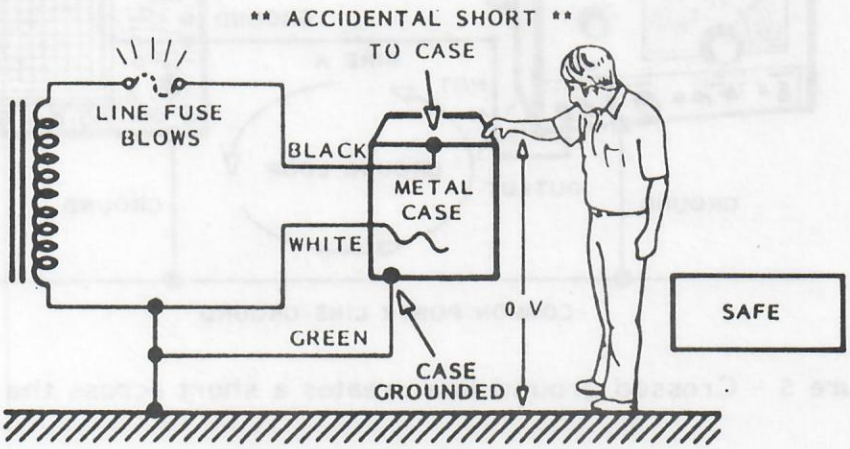
Figure 3 - Correct power outlet wiring.

The standard color code for electrical wiring, as shown in Figure 2, is BLACK for the hot line, WHITE for the neutral and GREEN for the ground line. With this plug arrangement, it is possible to ground the case of every instrument and appliance connected to the power line. This is an extremely important safety feature that should not be defeated. A three wire outlet as shown in Figure 3, ensures a good ground for the equipment. Figure 4(a) shows how the case of an ungrounded piece of test equipment that accidentally connects to the hot power line, is a shock hazard.

In Figure 4(a), with the ungrounded case, the person standing on a conducting ground, touching the metal test equipment case, is across the 117 volt power line and is subject to a deadly shock. In the circuit of Figure 4(b), the case is connected to ground through the third wire thus preventing the person touching that case from getting a shock. The third wire results in a short across the power line that will "blow" the circuit fuse or "kick-out" the circuit breaker to warn the operator of a fault in the equipment.



(a) UNGROUNDED CASE WITH SHORT TO CASE.



(b) GROUNDED CASE WITH SHORT TO CASE.

Figure 4 - Two and three wire plug systems.

Sometimes an instrument case is connected directly to the neutral line (white) using a two wire line cord and a polarized plug (one wide blade and one narrow blade). This system is safe until the plug has to be replaced and the new plug may not be polarized. Now, the case may be grounded when the plug is inserted one way and HOT if inserted in the reverse manner. There may also be a problem if the duplex outlet wiring was reversed when it was installed.

GROUND LOOPS

While the three wire connector system is necessary for power line safety, it sometimes interferes with electrical measurements that have to be made when the equipment under test and the test instruments are all grounded through three wire plugs. Crossed ground lines can produce wrong instrument readings, short circuits and burned out parts if not clearly understood and prevented.

All test instruments that have metal cases, tie the case to the power cord ground wire for safety. Many of these same test instruments that have ground connections for input and/or output circuits, also connect these grounds to the cabinet. This sometimes presents a problem as shown in Figure 5.

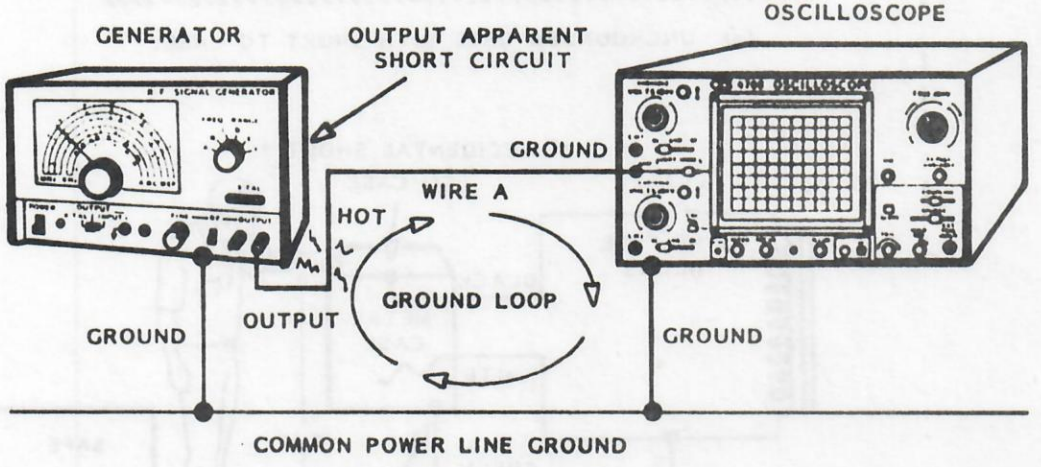


Figure 5 - Crossed ground line creates a short across the generator output.

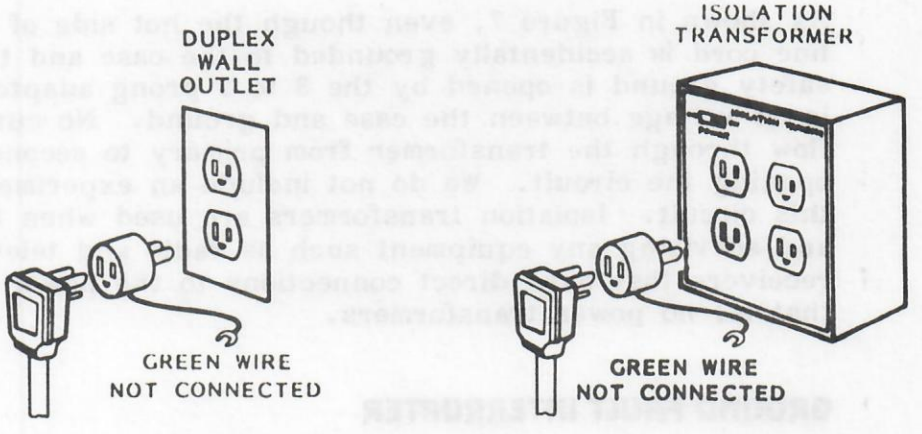
If the oscilloscope ground (wire A) is connected to the HOT or HIGH output terminal of the generator, it places a short circuit across the output of that generator. Generally, this does not harm to the generator although it does short and eliminate the output signal. It also prevents the oscilloscope from displaying the generator output since it is shorted. To prevent this problem some manufacturers isolate the input and/or output ground terminal from the case and power line ground system. This isolation is the approach used on the Ed-Lab Electronics Trainer; all grounds on the panel are isolated from the power line and power line ground. Thus, reversal of the two oscilloscope input leads does not short the generator output. The metal panel of the trainer is connected to earth ground and power line ground for safety.

GROUND LOOP VOLTAGES

Even when the instruments, that operate from the power line, do not have an input terminal grounded to the metal case, there may be false or wrong readings under certain conditions. This is caused by 60 Hz voltage differences due to small voltage drops along the ground line. This will be observed in this experiment when the reading of an ac voltmeter that is powered from the line (an FET VOM typically) changes value when the test leads are reversed or the circuit ground is removed.

GROUND ISOLATION

The elimination of short circuits due to third wire grounds can be accomplished by the use of a "3 prong to 2 prong adapter" such as shown in Figure 6. By leaving the green wire "floating" or unconnected, the instrument case is no longer grounded. This approach, however, as noted in Figure 6(a), is dangerous because it converts the safe conditions shown earlier in Figure 4(b) to the unsafe state shown in Figure 4(a).



(a) UNSAFE GROUND ISOLATION (b) SAFE GROUND ISOLATION

Figure 6 - Method of breaking a ground loop and avoiding shorts.

By using the 3 prong to 2 prong adapter and an ISOLATION TRANSFORMER, the equipment is isolated from the hot power line and there is no shock hazard even though the third wire ground has been removed. The circuit illustrating this safe condition is shown in Figure 7.

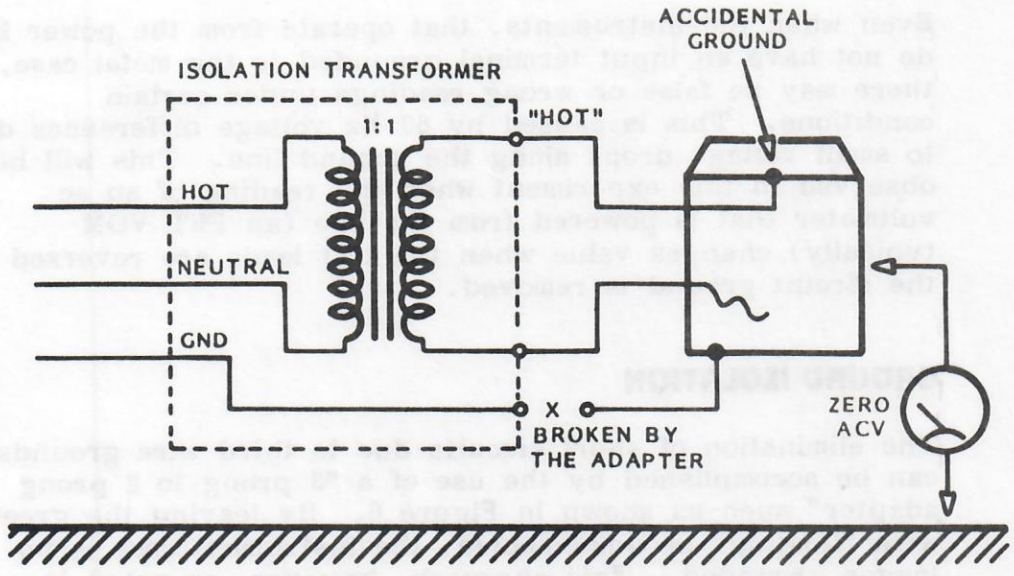


Figure 7 - Circuit of adapter and isolation transformer.

As shown in Figure 7, even though the hot side of the power line cord is accidentally grounded to the case and the safety ground is opened by the 3 to 2 prong adapter, there is no voltage between the case and ground. No current can flow through the transformer from primary to secondary thus opening the circuit. We do not include an experiment using this circuit. Isolation transformers are used when testing and servicing any equipment such as radio and television receivers that have direct connections to the power line, that is, no power transformers.

GROUND FAULT INTERRUPTER

There are occasions when a technician working on electrical or electronic equipment may be well grounded such as in area that has a wet concrete floor (basements or bathrooms) thus providing a conduction path to the power line ground. If the technician, or anyone, accidentally touches the hot side of the power line while grounded, there is a chance of a deadly shock. In an attempt to prevent this type of shock hazard, a device is used that is called a "Ground Fault Interrupter" or simply a GFI. The GFI shuts off the power to a line, automatically, when the current in the hot line is not very close in value to the current in the neutral line. The normal current distribution in the three wire power line is shown in Figure 8.

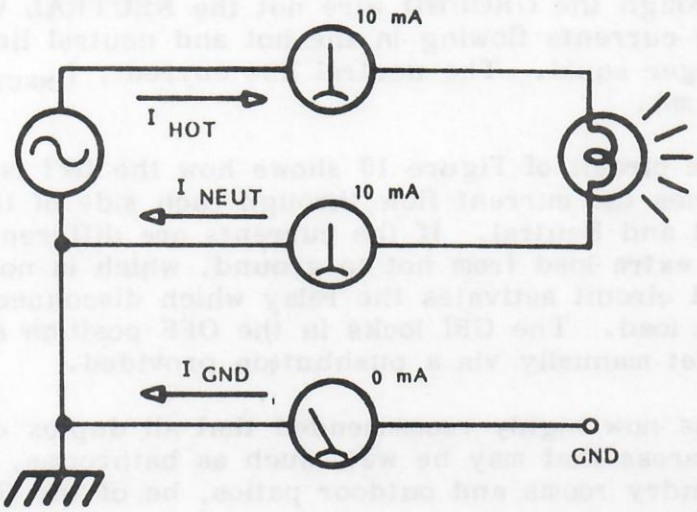


Figure 8 - Normal current distribution on a 3 wire line cord.

As shown in Figure 8, the load draws 10 mA causing a 10 mA current flow in both the hot and neutral lines. Note that there is no current flow in the ground line.

When a person accidentally contacts the hot line when grounded, as shown in Figure 9, the current distribution is upset. If 5 mA flows through the person the current distribution in the power lines change as shown in Figure 9.

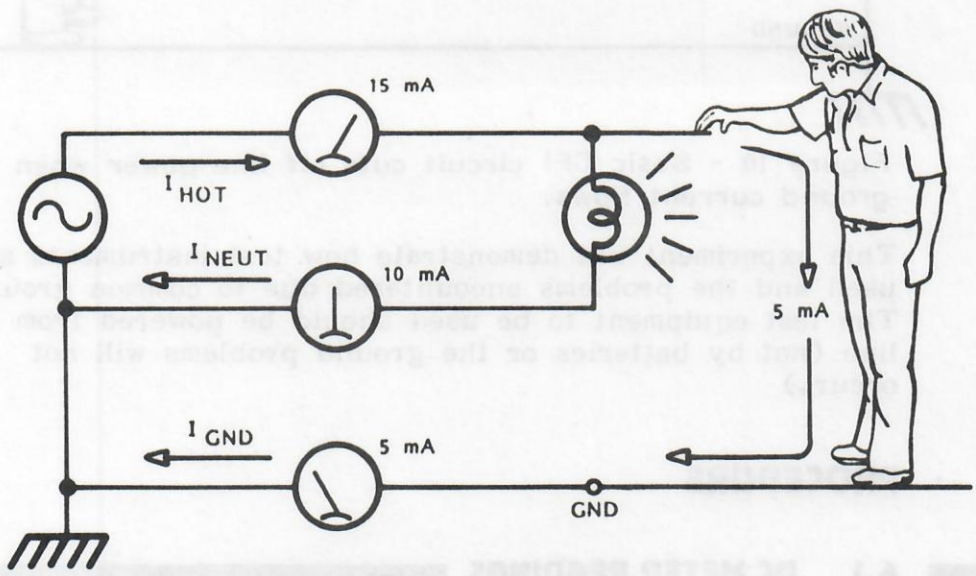


Figure 9 - Current distribution with person grounded.

Note that the current in the hot line has increased by 5 mA to 15 mA and this additional 5 mA returns to the source through the GROUND wire not the NEUTRAL wire. As a result, the currents flowing in the hot and neutral lines are no longer equal. The neutral line current, I_{NEUT}, remains at 10 mA.

The circuit of Figure 10 shows how the GFI is placed in series the current flow through each side of the power line, Hot and Neutral. If the currents are different, indicating an extra load from hot to ground, which is not allowed, the GFI circuit activates the relay which disconnects power from the load. The GFI locks in the OFF position and must be reset manually via a pushbutton provided.

It is now highly recommended that all duplex outlets located in areas that may be wet, such as bathrooms, kitchens, laundry rooms and outdoor patios, be of the GFI type.

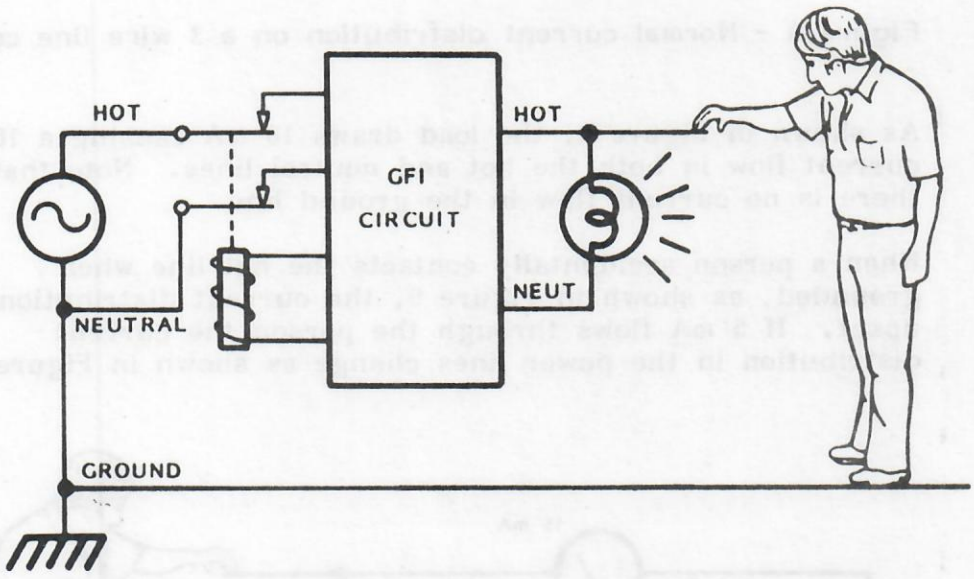


Figure 10 - Basic GFI circuit cuts off line power when a ground current flows.

This experiment will demonstrate how test instruments are used and the problems encountered due to common grounds. The test equipment to be used should be powered from the ac line (not by batteries or the ground problems will not occur.)

PROCEDURE

6.1 DC METER READINGS

1. Wire the circuit shown in Figure 11. Use the left and right hand resistors as marked.

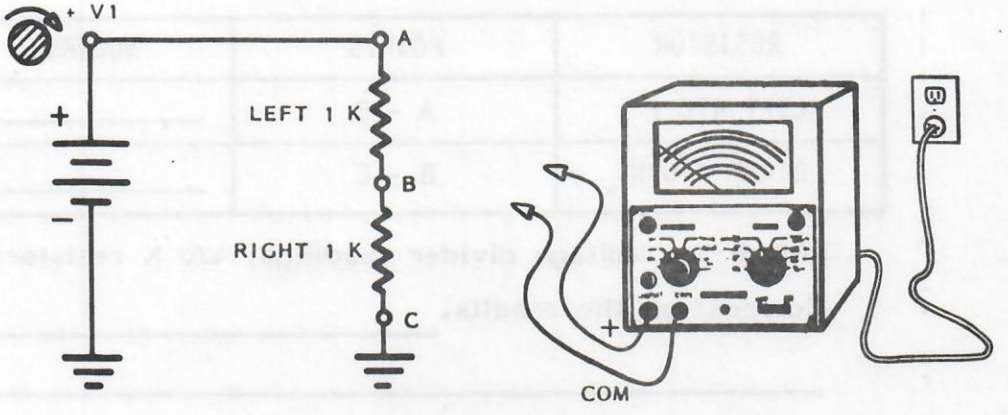


Figure 11 - DC voltage divider; EXPERIMENT.

The above voltage divider circuit provides an output from B to C that is one half of the applied voltage, +V1.

2. Use the external meter to measure the circuit voltages. Select an approximate voltage scale (10 volts).

   Connect the meter to read the +V1 input voltage (between +V1 and ground or between A and C) and adjust +V1 so that the voltage reads exactly 8 volts.

3. Connect the meter into the circuit to read the voltages across each resistor and record the readings in Table 1.

RESISTOR	POINTS	VOLTAGES
LEFT 1K	A - B	_____ V
RIGHT 1K	B - C	_____ V

TABLE 1 - Voltage divider readings; 1 K resistors.

Comment on the results. _____

_____

_____

4. Substitute 470 K resistors for the two 1 K resistors in the circuit of Figure 11. Measure the input voltage. It should still be 8 volts but if not, adjust +V1.

5. Measure the voltage drops across each resistor again and enter the readings in Table 2.

RESISTOR	POINTS	VOLTAGES
LEFT 470 K	A - B	_____ V
RIGHT 470 K	B - C	_____ V

TABLE 2 - Voltage divider readings; 470 K resistors.

Comment on the results. _____

_____

_____

What would occur if a 20 K/ΩV analog meter were used to measure the voltages in the circuit? _____

_____

_____

6.2 AC GENERATOR AND METER

6. Wire the external Audio Generator and the FET (Transistor) Multimeter to a voltage divider circuitr as shown in Figure 12. Set the Audio Generator for 5 kHz Sine Wave at maximum output.

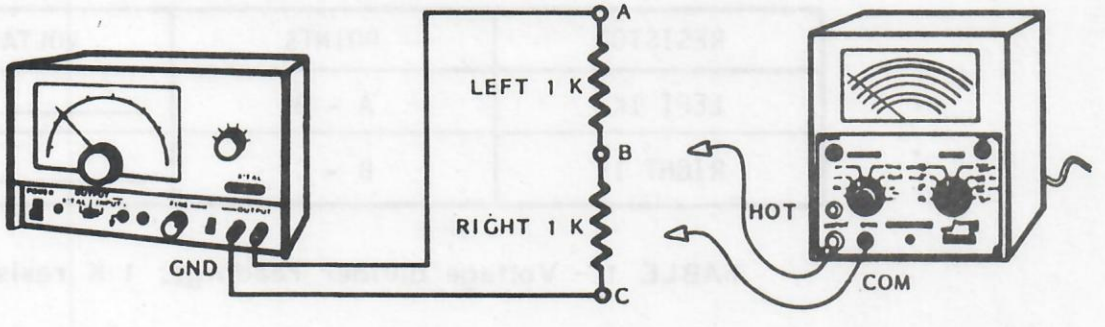


Figure 12 - Ac signal source measurement EXPERIMENT.

7. Connect the meter across the entire input signal (A to C) with the meter common (COM) connected to the generator ground, C.

8. With the generator set at 5 kHz, adjust the generator output level to 3 volts rms.

What meter range scale did you use? _____

How many ac voltage ranges are there on the meter used?

_____

What is the frequency range of the audio frequency generator you are using? _____

9. Take four voltage readings across the two resistors in Figure 12 as outlined in Table 3.

RESISTOR	POINTS		VOLTAGE
	GROUND LEAD	HOT LEAD	
RIGHT 1 K	C	B	_____ V
RIGHT 1 K	B	C	_____ V
LEFT 1 K	B	A	_____ V
LEFT 1 K	A	B	_____ V

TABLE 3 - Ac voltage readings for Figure 12.

Comment on the results. _____

_____

_____

_____

_____

10. Substitute two 470 K resistors for the 1 K resistors in the circuit. Readjust the input to 3 volts rms as read on the external meter.

Repeat the voltage measurements across each of the resistors as directed in Table 1 and enter the readings.

RESISTOR	POINTS		VOLTAGE
	GROUND LEAD	HOT LEAD	
RIGHT 470 K	C	B	_____ V
RIGHT 470 K	B	C	_____ V
LEFT 470 K	B	A	_____ V
LEFT 470 K	A	B	_____ V

TABLE 4 - Ac voltage readings with 470 K resistors.

Comment on the results. _____

_____

_____

_____

_____

11. Two capacitors wired in series will act as a voltage divider in an ac circuit. If the capacitors are equal in value, the voltage drop across each will be the same.

    Wire the circuit shown in Figure 13 and set the generator at 5 kHz with maximum output.

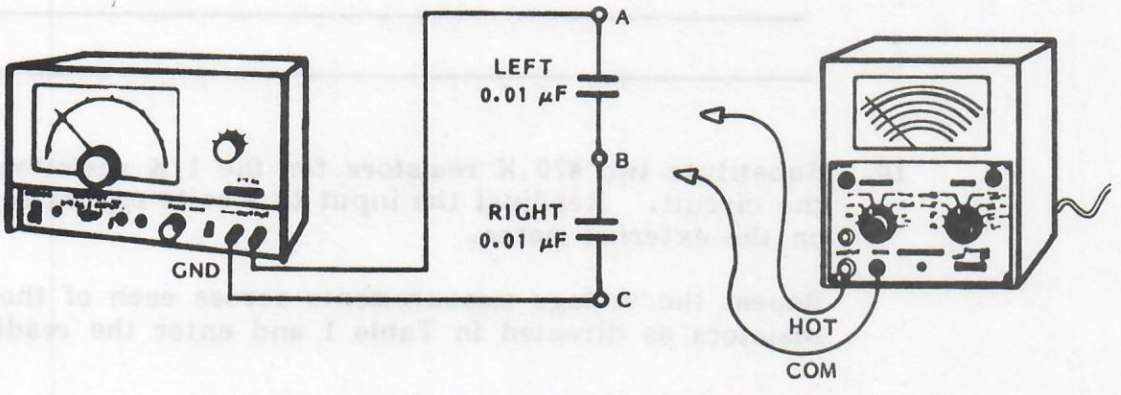


Figure 13 - Ac voltage divider EXPERIMENT.

12. Set the meter to ac operation on the 10 volt scale.

    Connect the meter across the generator output (A to C with the COMMON lead to ground) and adjust the sine amplitude to 2 volts rms.

13. The expected voltage drop across each capacitor is 1 volt rms. Measure all the voltage drops as directed in Table 5.

RESISTOR	POINTS		VOLTAGE
	GROUND LEAD	HOT LEAD	
RIGHT 0.01 μF	C	B	_____V
RIGHT 0.01 μF	B	C	_____V
LEFT 0.01 μF	B	A	_____V
LEFT 0.01 μF	A	B	_____V

TABLE 5 - Ac voltage readings with a capacitor divider.

Comment on the results. _____

_____

_____

_____

_____

_____

_____

_____

14. Remove the external generator and assemble the circuit shown in Figure 14 using the Function Generator and ac meter on the Ed-Lab Trainer.

Set the Function Generator to 5 kHz and the meter switch to 5 VAC as shown.

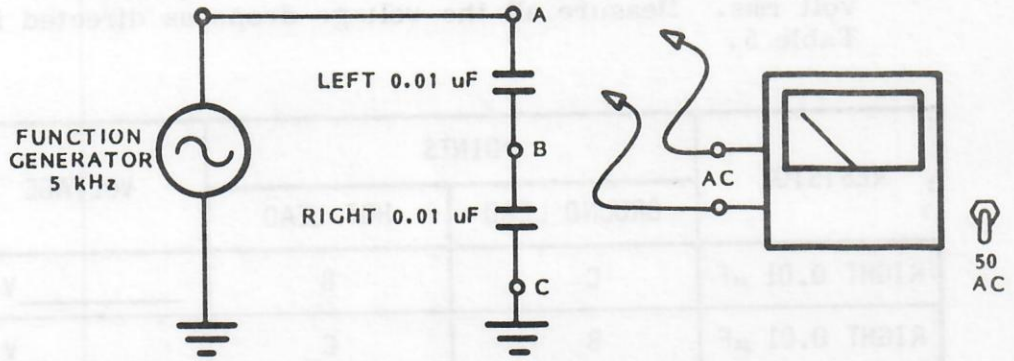


Figure 14 - Ed-Lab ac measurement EXPERIMENT.

15. Connect the meter leads to A and to C and adjust the Function Generator SINE AMPL. control for a reading of 2 volts rms. Now measure the circuit voltages as directed in Table 6.

CAPACITOR	POINTS		VOLTAGE
	R JACK	Y JACK	
RIGHT 0.01 μF	C	B	_____ V
RIGHT 0.01 μF	B	C	_____ V
LEFT 0.01 μF	B	A	_____ V
LEFT 0.01 μF	A	B	_____ V

TABLE 6 - Ac voltage readings using Ed-Lab instruments.

Comment on the results._____

_____

_____

_____

6.3 GENERATOR OUTPUT RESISTANCE

16. All generators have an internal Source Resistance, labelled R_S, in their output circuit as shown schematically in Figure 15.

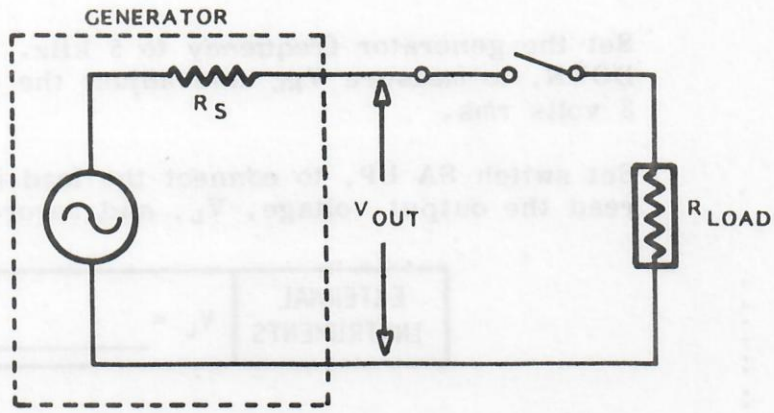


Figure 15 - Generator source and load resistances.

To measure the internal resistance of any source, a load is placed on the generator as shown in Figure 15 and the loaded (V_L) and no-load (V_{NL}) output voltages are measured. Since R_S and R_L form a voltage divider, the voltage divider formula, introduced in DC Circuits, Unit E4, Experiment Number 21, may be used to solve for the value of R_S, given that R_L is known and V_L and V_{NL} are easily measured. The voltage divider equation is:

$$V_{RL} = V_{NL} \frac{R_L}{R_L + R_S}$$

Transposing to solve for R_S, we have:

$$R_S = R_L \frac{(V_{NL} - V_L)}{V_L}$$

17. Connect the external audio generator and the external meter to the circuit shown in Figure 16.

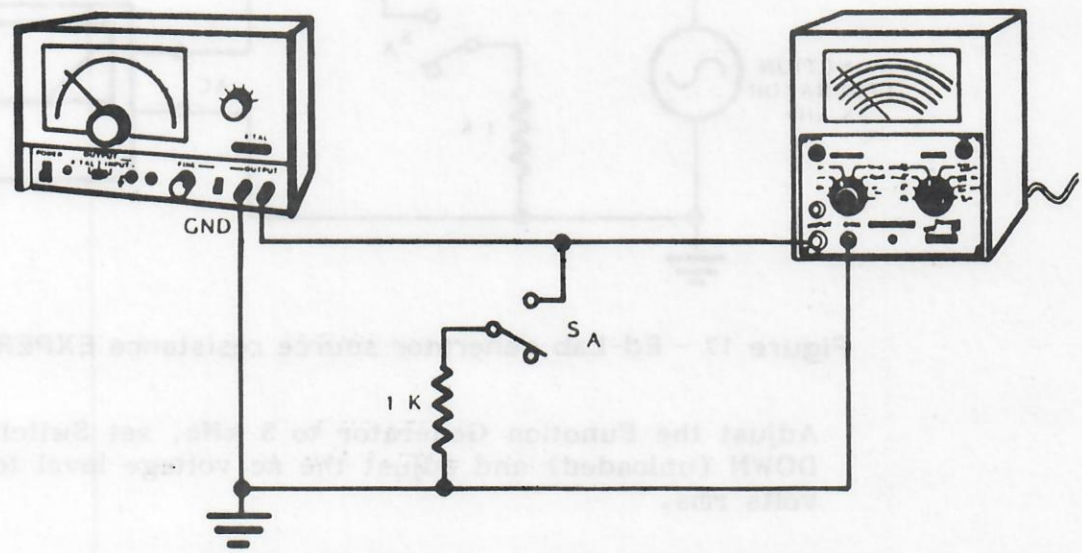


Figure 16 - External generator R_S measurement EXPERIMENT.

Set the generator frequency to 5 kHz. Set Switch SA DOWN, to measure V_{NL} and adjust the generator output to 3 volts rms.

Set switch SA UP, to connect the load into the circuit; read the output voltage, V_L, and record it below.

EXTERNAL INSTRUMENTS	V_L = _____ V

18. Calculate the output resistance, R_S, of the external generator.

$$R_S = 1000 \frac{(3 - V_L)}{V_L}$$

$$= 1000 \frac{(3) - (\quad)}{(\quad)}$$

R_S = _____ ohms

19. Repeat the above measurements using the Ed-Lab Function Generator and panel meter.

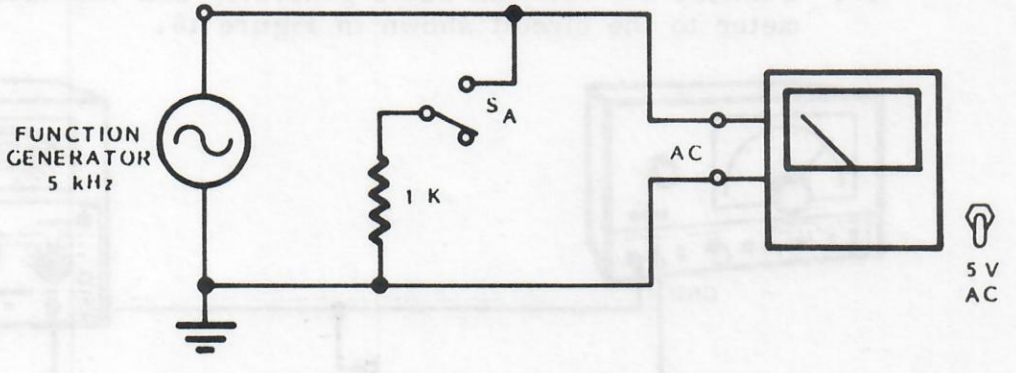


Figure 17 - Ed-Lab generator source resistance EXPERIMENT.

Adjust the Function Generator to 5 kHz, set Switch SA DOWN (unloaded) and adjust the ac voltage level to 3 volts rms.

20. Set Switch SA UP to connect the load and measure the loaded voltage, V_L.

ED-LAB INSTRUMENTS	V_L = _____ V

21. Solve for the value of R_S, the source resistance.

$$R_S = 1000 \frac{(3 - V_L)}{V_L} \quad \text{(From Step 18)}$$

$$= 1000 \frac{(3) - (\quad)}{(\quad)}$$

R_S = _____ ohms

Which source resistance is better? Explain why._____

_____

_____

_____

6.4 SIGNAL SHORTING GROUND LOOP

22. When all the test instruments have a "third wire" ground, it is possible to develop short circuits across the signal source. This is illustrated in the following steps.

Connect the oscilloscope to the Function Generator output as shown in Figure 18. Observe that the CH 1 input line is grounded and that the oscilloscope ground is connected to the generator output.

Does the oscilloscope display the 1 kHz output even though the oscilloscope leads are reversed?_____

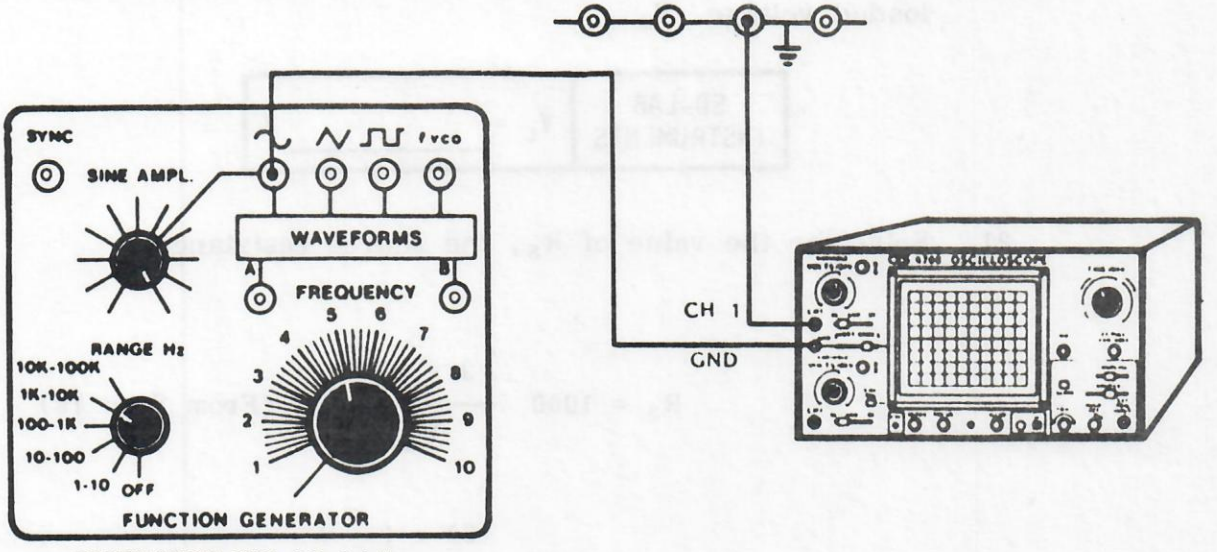


Figure 18 - Oscillocope connected to trainer with reserved leads; EXPERIMENT.

23. Connect a jumper wire from the Earth ground jack to the ground line as shown in Figure 19, and observe the oscilloscope display.

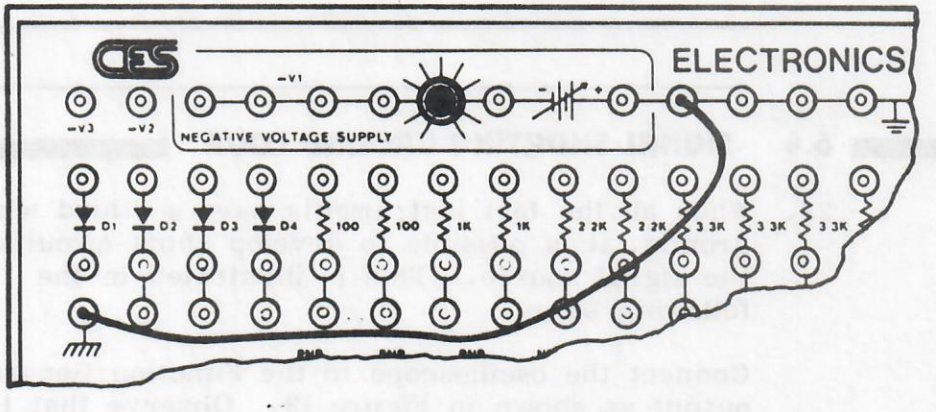


Figure 19 - Earth ground connection to the trainer ground system; EXPERIMENT.

What happended to the oscilloscope display? _____

_____

Explain why. _____

_____

24. Reverse the connections to the oscilloscope input, ground to ground and CH 1 to the Function Generator Sinewave output.

Does the signal reappear on the oscilloscope screen? _____

It is apparent then, if both the signal source and the oscilloscope are at earth ground potentials, reversing the oscillocope leads places a short across the signal source output. The use of an isolation transformer in the Ed-Lab trainer allows lead polarities to be switched without loss of signal.

6.5 AC POWERED FET METER ERROR

The meters powered from the ac line, as shown earlier, will introduce errors in the ac voltage readings unless the proper lead connection polarity is observed. In this part of the procedure you will observe the effects caused by reversed leads in a reactive circuit and then use an oscilloscope to measure the voltage.

25. Wire the circuit shown in Figure 20.

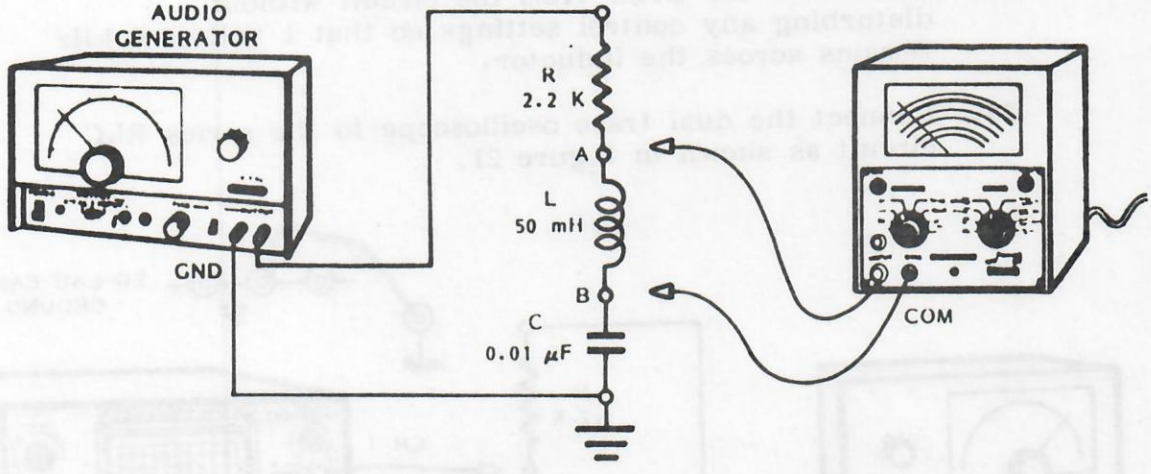


Figure 20 - Series RLC circuit EXPERIMENT

26. Set the meter on the 3 V AC range and adjust the Audio Generator frequency to 4 kHz and adjust the output level until the meter reads 1 volt.

27. Reverse the meter polarity, placing the common lead at point A and the hot lead at point B. Read and record the new voltage reading in the space provided on the next page.

REVERSED METER LEADS	V_{ac} = _____ V

What has ocurred? _____

_____

The error will be close to fifteen percent and so requires that the voltmeter common or ground lead always be placed closest to ground, Point B in Figure 20. Because of the possibility of error introduced by the ground loops when the meter is powered from the ac line, it is often more convenient to use battery powered meters or a dual trace oscilloscope as outlined in the next procedure.

6.6 DUAL TRACE OSCILLOSCOPE METHOD

28. Disconnect the meter from the circuit without disturbing any control settings so that 1 volt at 4 kHz remains across the inductor.

29. Connect the dual trace oscilloscope to the series RLC circuit as shown in Figure 21.

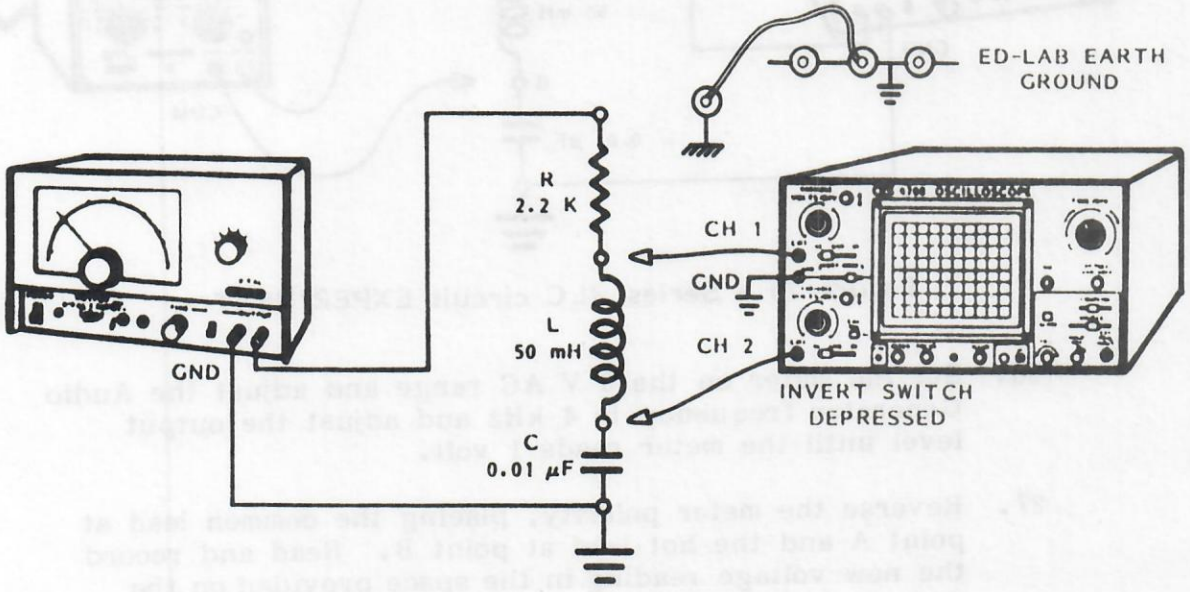


Figure 21 - Dual trace oscilloscope measurement technique; EXPERIMENT.

30. You will use the dual trace oscilloscope in the subtraction mode. Set the controls as follows:

CH 1	V/DIV	1 V	TIME/DIV	0.2 mS
CH 2	V/DIV	1 V	SOURCE	CH 1
CH 2	INVERT	INVERT (IN)	VERT MODE	ADD

(All Variable controls must be in the Calibrate position).

Adjust the oscilloscope for a stable display.

31. Read the ac peak-to-peak voltage as follows; Count the number of vertical divisions the trace covers and enter the number below.

VERTICAL DIVISIONS = _____

Calculate the peak-to-peak voltage from:

$$V_{Lp\text{-}p} = (\text{No. of Div.})(\text{V/DIV})$$

$$= (\quad)(1)$$

$V_{Lp\text{-}p}$ = _____ V

32. Convert the p-p voltage to rms so that it can be compared to the meter reading taken earlier.

$$V_{L\,rms} = \frac{VLp\text{-}p}{2}\ (0.707)$$

$$= \frac{(\quad)}{2}\ (0.707)$$

$V_{L\,rms}$ = _____ V

Is the oscilloscope voltage measurement close to the FET VOM reading of 1 volt?

_____

The FET meter may have actually disturbed the circuit so that the oscilloscope reading will be more accurate.

CONCLUSIONS

We have learned from this experiment that:

One side of the power line is connected to earth ground before the lines enter a building.

One side of the power line is grounded as a protection against lightning stikes.

The house power wiring color code is BLACK for the hot line, WHITE for the neutral line and GREEN for the ground wires.

The duplex outlet has three different shape connections, a wide blade for the neutral wire, a narrow blade from the hot and a round prong for the ground line.

The ground line is connected to the metal housing of all electrically powered devices such as appliances, test instruments and motors.

When the hot line accidentally makes contact with the metal case of a motor, test instrument or appliance, the line fuse will burn out if the case is grounded by the third wire.

It is dangerous to defeat the third wire ground type plug by using a 3 prong to 2 prong adapter without grounding the green wire.

An isolation transformer breaks the hot line path thus eliminating a shock hazard.

Ground loops can cause short circuits and blow fuses but will not endanger anyone if all the equipment metal cabinets are grouned.

A Ground Fault Interrupter circuit will cut off the power when any current flows in the ground line and the neutral and hot line currents are not balanced.

Ground loops can create erroneous (ac meter) readings if special care is not taken.

A dual trace oscillocope may be used to measure voltage across a series reactive component using the sum-difference technique.

ASSIGNMENT

Answer the following multiple choice questions.

1. One side of a power line is grounded just before it enters a building in order to:

   a. reduce shock hazard.
   b. minimize voltage surges due to lightning stikes on the power line.
   c. correct for ground loops.
   d. all of the above.

2. The standard household wiring color code is Black _____; White _____; Green _____.

   a. neutral; hot; ground.
   b. hot, neutral; ground.
   c. ground; hot; neutral.
   d. neutral; ground; hot.

3. The blade connector shapes of a duplex outlet are; Wide Blade _____; Narrow Blade _____; Round Blade _____.

   a. hot, neutral; ground.
   b. ground; hot; neutral.
   c. neutral; hot; ground.
   d. neutral; ground; hot.

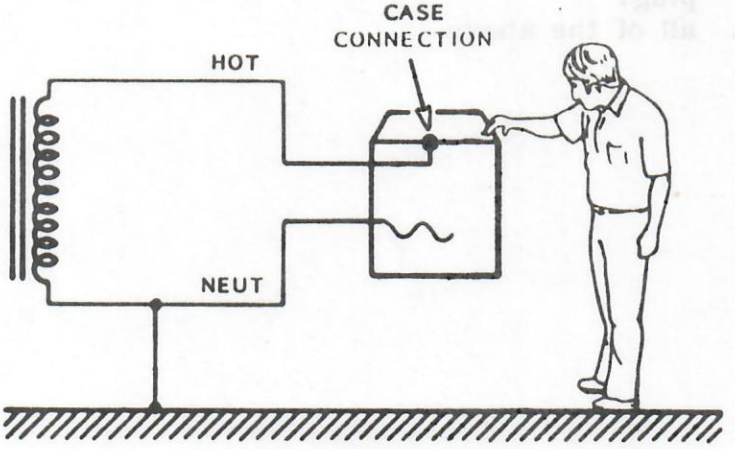


Figure 22 above refers to questions 4 and 5.

4. The person drawn in Figure 22:

   a. is receiving a possibly lethal shock.
   b. cannot receive a shock because he is firmly grounded.
   c. will get a shock but only a very slight one.
   d. none of the above.

5. The person drawn in Figure 22:

   a. is in danger of being electrocuted.
   b. could be protected by grounding the case with a third wire.
   c. could be saved from shock by switching the hot and neutral wires.
   d. all of the above.

6. Unintentional "ground loops" formed by connecting several pieces of equipment together, can:

   a. affect meter readings.
   b. create short circuits.
   c. both (a) and (b).
   d. neither (a) nor (b).

7. The third wire ground should be removed, if necessary, (following all safety precautions) from a power plug by:

   a. using an adapter and not grounding the green wire.
   b. using an adapter and grounding the green wire.
   c. hack sawing off the round pin (ground) on the power plug.
   d. all of the above.

KEY TERMS

1. ADAPTER (3 prong to 2 prong)

   A device used to change the three prong terminal arrangement of a power plug to a 2 prong arrangement so that it will fit in the old two prong receptacles or break the ground path when desired (an unsafe procedure).

2. EARTH GROUND

   A conductor connected from the circuit ground to a pipe driven into the soil.

3. GROUND WIRE

   The wire in a power distribution system that connects to earth ground. Also the common voltage reference point in a circuit.

4. GROUND LOOP

   A complete electrical circuit caused by multiple grounds.

5. HOT LINE

   That wire in the power distribution system that carries the voltage with respect to ground.

6. ISOLATION TRANSFORMER

   A transformer that couples a load to the power line through magnetic coupling thus isolating the load from the hot and neutral lines. The transformer normally has a 1:1 turns ratio.

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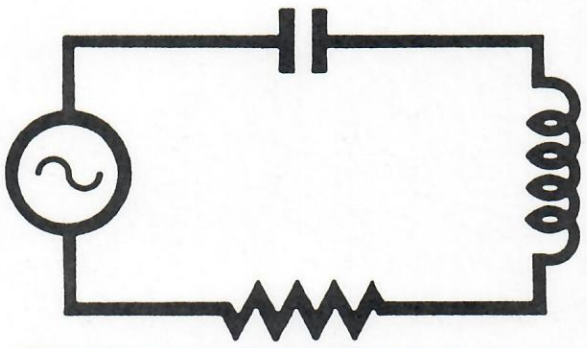
Text-Lab Manual
G4 - AC RLC CIRCUITS



G4

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PART G4

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CES INDUSTRIES, INC.
Educational Products Division
130 Central Avenue
Farmingdale, New York 11735
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Experiment	8	Series RLC Circuit Voltages

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STUDENT PROGRESS & RECORD GUIDE FOR AC PART G4

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Name _____

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Date _____

STUDENT PROGRESS & RECORD GUIDE FOR AC PART 04

EXP./INFO.	TITLE	ASSIGNMENT DATE DUE	ASSIGNMENT DATE SUBMITTED	GRADE
Experiment 1	Inductive Reactance			
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Experiment 7	Series Resonant Circuits			
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Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part G1. Review this lesson.

Ed-Lab
TEXT-LAB MANUAL
AC RLC CIRCUITS
PART G4

Inductive Reactance 1

OBJECTIVES

When you finish this experiment, you will be able to:

1. Determine the current flow in an RL circuit.
2. Calculate X_L from the measured values in the RL circuit.
3. Calculate the theoretical value of X_L.
4. Demonstrate the RL circuit voltage division characteristics for various frequencies.
5. Plot reactance as a function of frequency to demonstrate the linear characteristics of X_L.

DESCRIPTION

The opposition that an inductor offers to a changing current has been shown to be due to the counter electromotive force (CEMF) developed by that inductor. The larger the inductance value (in henries), the greater the opposition to the changing current because a larger CEMF is developed. It is, however, awkward to measure the opposition to a current by the amount of CEMF developed. It is more normal to measure the opposition to the flow of a current in ohms.

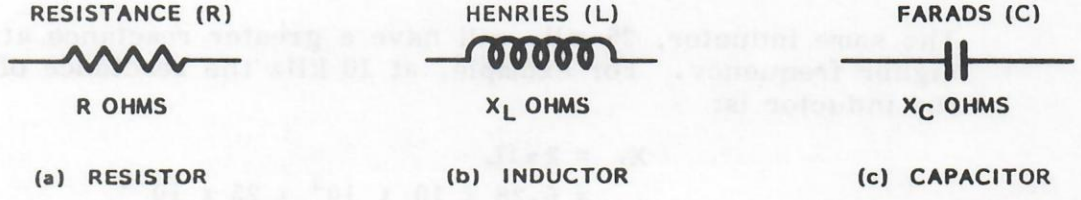


Figure 1 - Opposition to the flow of current.

The opposition to current flow in a dc circuit was called resistance, identified by the letter R and measured in ohms.

The "reaction" of the inductor to the flow of a changing or alternating current (ac) is called REACTANCE and is also measured in ohms. Reactance is identified by the letter X, and to indicate that it is an inductive reactance it is further identified as X_L. Thus, the opposition to the flow of alternating current through an inductor is called INDUCTIVE REACTANCE, it is designated X_L and it is measured in ohms.

The opposition to ac current flow through a capacitor is called CAPACITIVE REACTANCE. It is designated as X_C, also measured in ohms and it will be studied in the next experiment.

INDUCTIVE REACTANCE

The more rapid the rate of change of an alternating current, the greater the CEMF developed by the inductor and so the greater the reactance. The rate of change of an ac waveform is a function of the frequency of that ac. The higher the frequency, the greater the rate of change and the greater the rate of change, the greater the inductive reactance. The reactance of an inductor is defined as:

INDUCTIVE REACTANCE	$X_L = 2\pi fL$

where X_L = inductive reactance in ohms
2π = 6.28
f = frequency in Hz
L = inductance in henries

For example, a 25 mH inductor at 5 kHz will have a reactance, X_L, of:

$$X_L = 2\pi fL$$
$$= 6.28 \times 5 \times 10^3 \times 25 \times 10^{-3}$$
$$= 6.28 \times 5 \times 25$$

f = 5 kHz	X_L = 785 ohms

The same inductor, 25 mH, will have a greater reactance at a higher frequency. For example, at 10 kHz the reactance of the inductor is:

$$X_L = 2\pi fL$$
$$= 6.28 \times 10 \times 10^3 \times 25 \times 10^{-3}$$
$$= 6.28 \times 10 \times 25$$

f = 10 kHz	X_L = 1570 ohms

LINEAR RELATIONSHIP

Observe that an increase in frequency of 2 times (5 kHz x 2 = 10 kHz) resulted in an increase in X_L of 2 times (785 x 2 = 1570 ohms). We can conclude from this that X_L and f have a LINEAR relationship which means a straight line graph when X_L is plotted against frequency for a given value of L. This is shown in Figure 2.

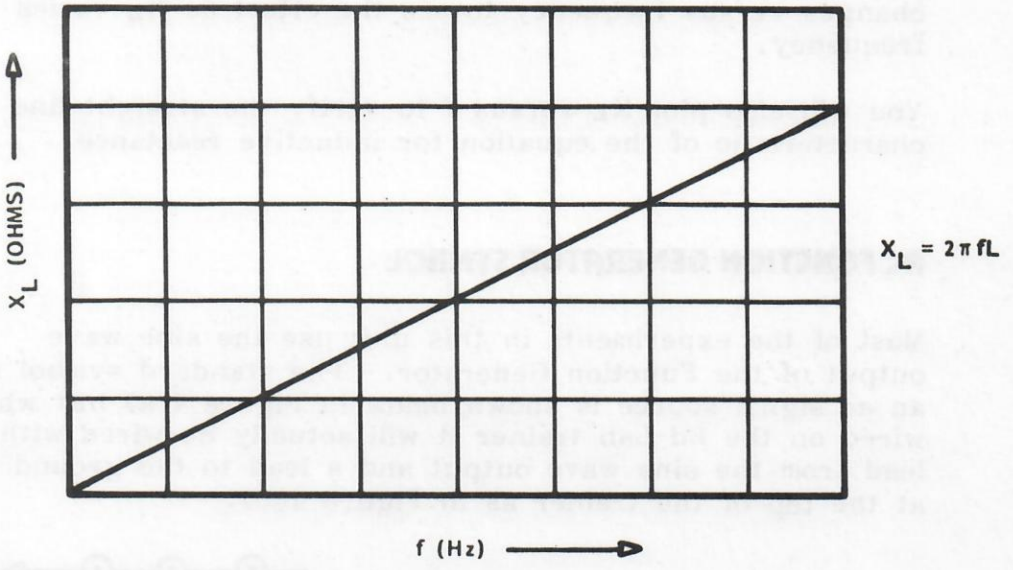
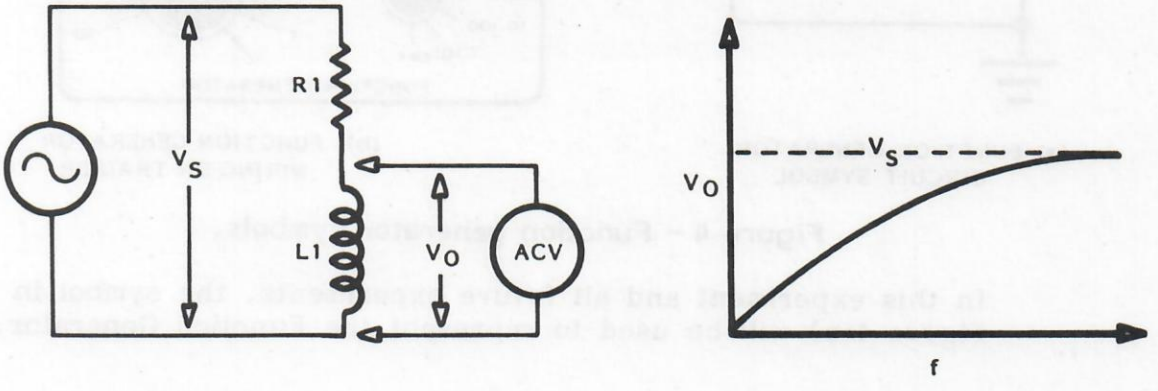


Figure 2 - A theoretical plot of X_L versus f will be linear.

INDUCTIVE VOLTAGE DIVIDER

Connecting an inductor in series with a resistor as shown in Figure 3 forms a voltage divider. The output of the voltage divider will increase with frequency because X_L rises with frequency. If the frequency is made high enough, almost the full input will appear at the output as shown in Figure 3 (b).



(a) INDUCTIVE VOLTAGE DIVIDER (b) Vo VERSUS f

Figure 3 - An inductive voltage divider.

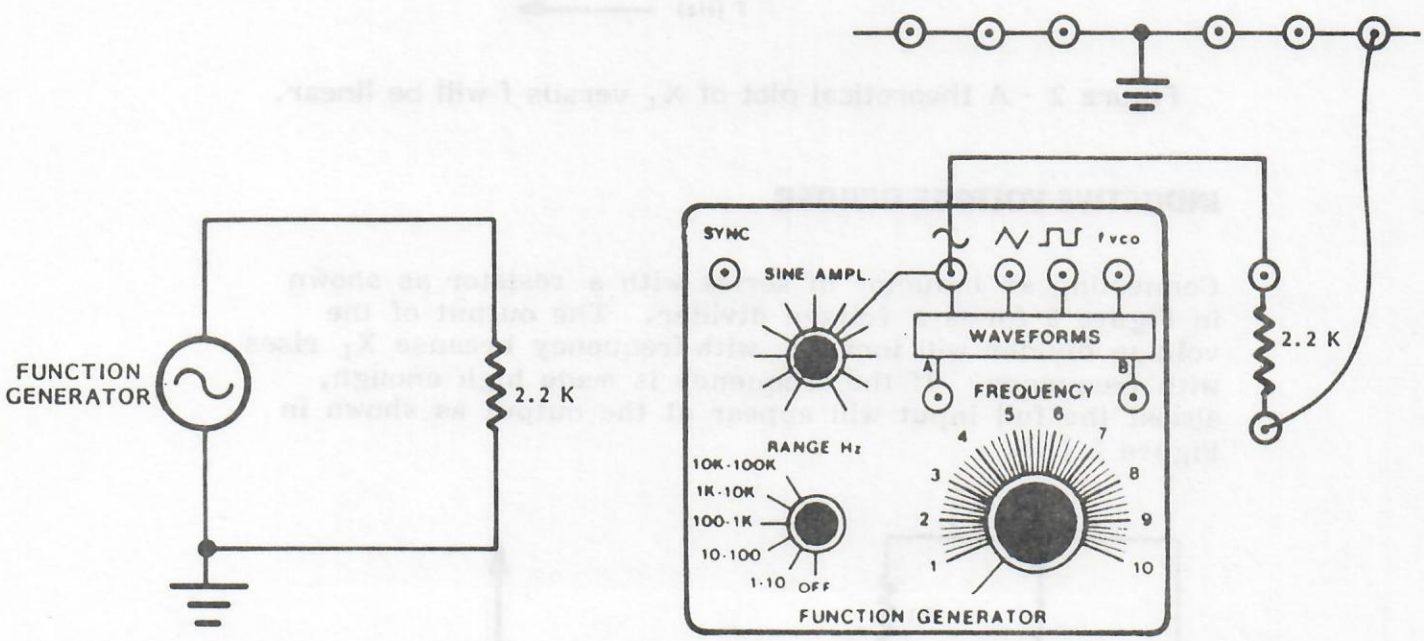
In this experiment, you will wire an RL voltage divider, connect it to an ac signal source (the Function Generator) and vary the frequency over a range of 1 kHz to 10 kHz. You will determine the current flow in the circuit for each input frequency and calculate X_L at each frequency.

Using the data collected, you will plot the output voltage changes versus frequency to see the effect as X_L varies with frequency.

You will also plot X_L versus f to verify the straight line characteristic of the equation for inductive reactance.

AC FUNCTION GENERATOR SYMBOL

Most of the experiments in this unit use the sine wave output of the Function Generator. The standard symbol for an ac signal source is shown below in Figure 4(a) but when wired on the Ed-Lab trainer it will actually be wired with a lead from the sine wave output and a lead to the ground bus at the top of the trainer as in Figure 4(b).



(a) FUNCTION GENERATOR CIRCUIT SYMBOL

(b) FUNCTION GENERATOR WIRING ON TRAINER

Figure 4 - Function generator symbols.

In this experiment and all future experiments, the symbol in Figure 4(a) will be used to represent the Function Generator.

PROCEDURE

1. Wire the circuit shown in Figure 5. Observe that the standard sine wave signal source symbol is now in use for the Function Generator. With Switch SA UP, the

meter measures the voltage across the resistor, V_R. With Switch SA DOWN, the meter measures the output voltage across the inductor, V_L.

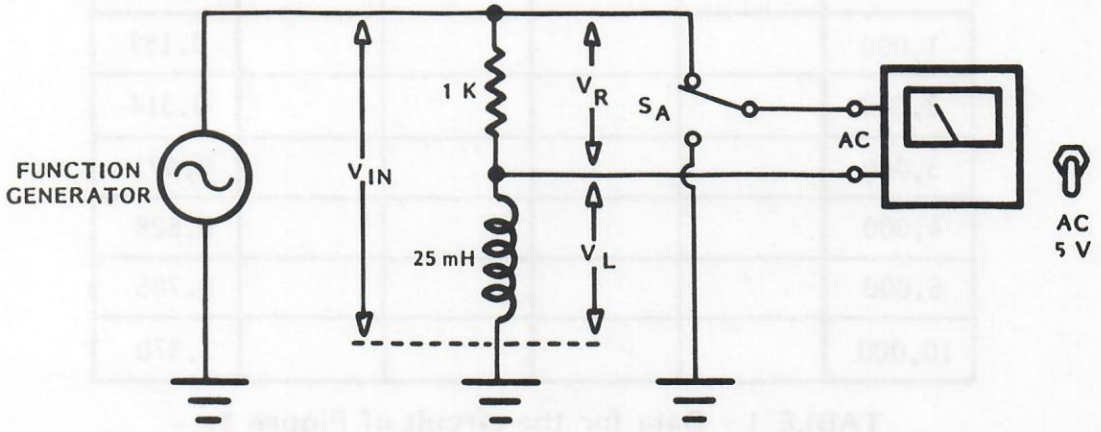


Figure 5 - Inductive voltage divider EXPERIMENT.

2. Adjust the Function Generator to 1 kHz on the 1K to 10K range.

   Set the SINE AMPL. control to maximum output.

1.1 VOLTAGE MEASUREMENTS

3. With the Function Generator set at 1 kHz, place Switch SA DOWN to measure the voltage across the coil, V_L, and record it in Table 1, column 2.

   Move Switch SA UP to measure the voltage across the resistance, V_R, and record it in Table 1, column 3.

SET	MEASURE		CALCULATE		COMPARE
1	2	3	4	5	6
f (Hz)	V_L SA DOWN	V_R SA UP	$I_R = I_L$ (mA)	$X_L = \frac{V_L}{I_R}$ (K OHMS)	$X_L = 2\pi fL$ (K OHMS)
1,000					0.157
2,000					0.314
3,000					0.471
4,000					0.628
5,000					0.785
10,000					1.570

TABLE 1 - Data for the circuit of Figure 5.

4. Repeat the voltage measurements across L and R for each frequency listed in column 1 of Table 1 and enter the results in Table 1.

1.2 CALCULATING X_L

5. Using the data from Table 1, calculate I_R for each frequency as follows:

$$I_R = \frac{V_R}{R} \quad \text{where R = 1000 ohms = 1 K ohms}$$

Because R is 1 K, the answer to each computation will be in milliamperes exactly equal to the voltage V_R. For a V_R of 4.2 volts, I will equal 4.2 mA.

$$I_R = \frac{V_R}{R} = \frac{4.2\ V}{1\ K} = 4.2\ mA$$

Enter the current values, I_R, in column 4 of Table 1 by copying the values from column 3.

6. Because R and L are in series, the currents in R and L are the same; I_R equals I_L. With both I_L and V_L known, X_L may be calculated from the ac versions of Ohm's Law.

Ohm's Law $$R = \frac{E}{I}$$

becomes $$X_L = \frac{V_L}{I_L}$$

Calculate X_L for each frequency by dividing V_L (column 2) by I (column 4) and enter the results in Table 1, column 5. Remember, if I_L is entered in mA, the resistance is read in KΩ.

1.3 THEORETICAL X_L

7. The theoretical values of X_L were calculated from

$$X_L = 2\pi fL$$

for each frequency and the results have been entered in column 6 of Table 1.

Are the theoretical reactance values in column 6 close to the measured reactance values?

_____

To what do you attribute any difference between the calculated and theoretical reactance values?

_____

_____

_____

1.4 OUTPUT VOLTAGE RESPONSE PLOT

8. Plot the output voltage, V_O, of the circuit in Figure 4, as a function of frequency, on the graph shown in Figure 6. (Remember, the output voltage V_O is V_L.) Observe how the output voltage varies with frequency as X_L changes.

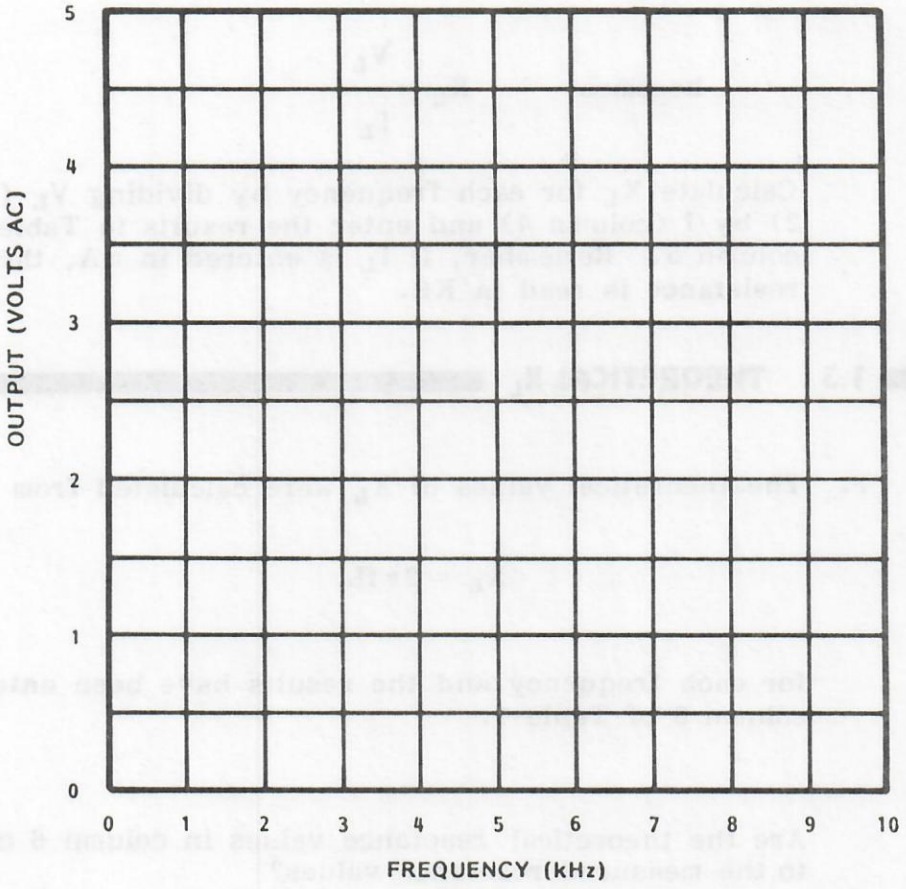


Figure 6 - Plot of V_{OUT} versus generator frequency.

1.5 PLOTTING X_L VERSUS FREQUENCY

10. Plot the theoretical reactance points (column 6, Table 1) versus frequency on the graph in Figure 7. Circle the points and draw a "best straight line."

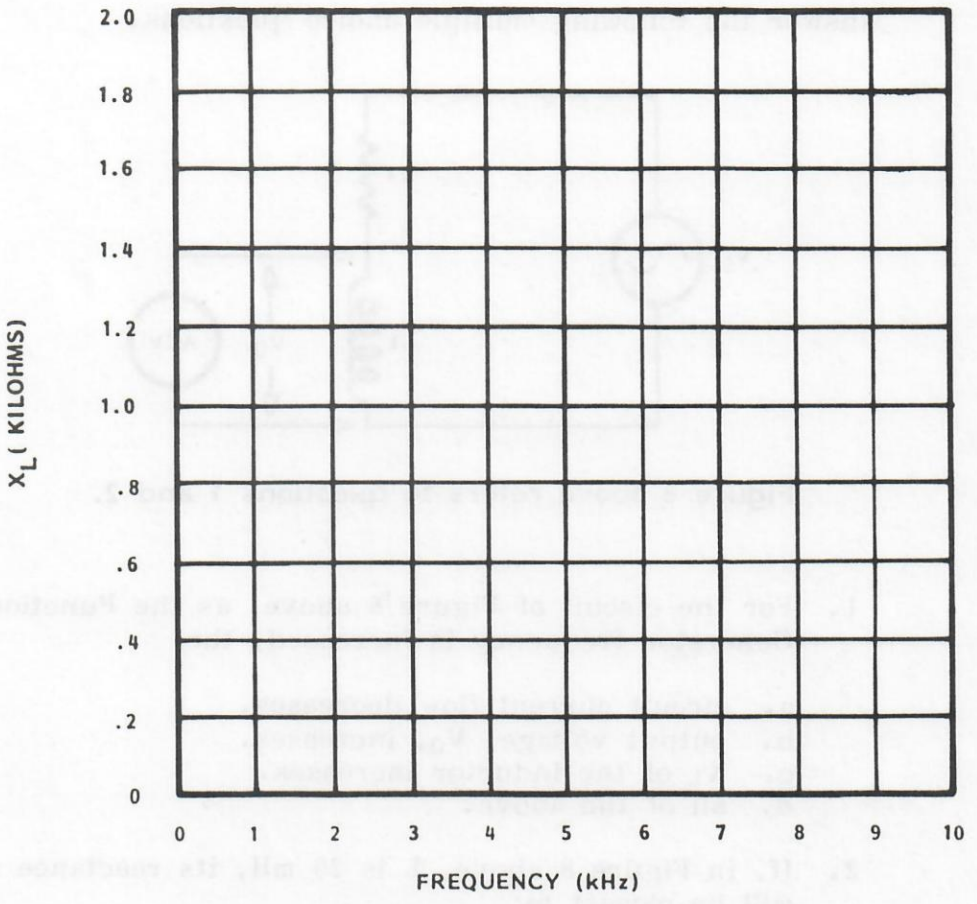


Figure 7 - Plot of theoretical reactance versus frequency.

10. Plot the points corresponding to the measured values of X_L (column 5 of Table 1) on the graph of Figure 7.

How do the measured points follow the theoretical linear line?

CONCLUSIONS

We have learned from this experiment that:

X_L increases with frequency.

X_L increases at a linear rate as frequency increases.

The current flow in a series R-L circuit such as in Figure 3 will decrease as the frequency increases.

The output voltage, V_o in Figure 3, increases as the frequency is increased.

ASSIGNMENT

Answer the following multiple choice questions.

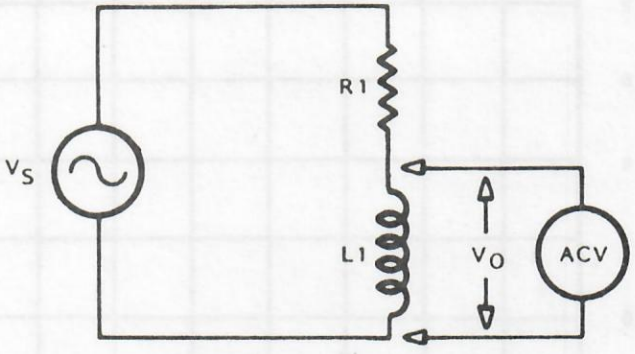


Figure 8 above refers to questions 1 and 2.

1. For the circuit of Figure 8 above, as the Function Generator frequency is increased, the:

   a. circuit current flow decreases.
   b. output voltage, V_O, increases.
   c. X_L of the inductor increases.
   d. all of the above.

2. If, in Figure 8 above, L is 20 mH, its reactance at 2 kHz will be closest to:

   a. 251,000 Ω.
   b. 12,500 Ω.
   c. 251 Ω.
   d. 125 Ω.

3. Inductive reactance varies:

   a. inversely with frequency.
   b. directly with the inductance value.
   c. when the series resistance value (Figure 8) is increased.
   d. none of the above.

4. Inductive reactance may be defined as:

   a. opposition to the flow of ac, measured in ohms.
   b. opposition to the flow of ac, measured in volts (cemf).
   c. being equal to its inductive value in henries.
   d. all of the above.

5. As the inductance of a coil is increased:

   a. its resistance decreases.
   b. its reactance, at a given frequency, decreases.
   c. its reactance, at a given frequency, increases.
   d. the constant 2π in the reactance formula must be increased.

KEY TERMS

1. COUNTER ELECTROMOTIVE FORCE (CEMF)

   A voltage developed across an inductor by a changing current. The voltage polarity is opposite in polarity to the applied voltage.

2. INDUCTIVE REACTANCE (X_L)

   The opposition to the flow of alternating current through an inductor. It is measured in ohms, indicated as X_L and calculated from $X_L = 2\pi fL$.

3. REACTANCE

   Opposition to the flow of alternating current. Reactance is measured in ohms and indicated as X.

Capacitive Reactance 2

OBJECTIVES

When you finish this experiment, you will be able to:

1. Determine the current flow in an RC circuit.
2. Calculate X_C from the measured values.
3. Calculate the theoretical value of X_C.
4. Demonstrate the RC circuit voltage division characteristic for various frequencies.
5. Plot capacitive reactance as a function of frequency.

DESCRIPTION

When the voltage that has been applied to a capacitor is changed, the capacitor charges or discharges until the capacitor voltage is equal to the applied voltage. When the capacitor voltage is equal to the applied voltage there is no longer any current flow. Since the capacitor reacts to an external voltage change by changing its own voltage, the capacitor is said to be REACTIVE. Reactance is defined by the letter X and since it is capacitive reactance, it is further identified as X_C and measured in ohms as shown in Figure 1.

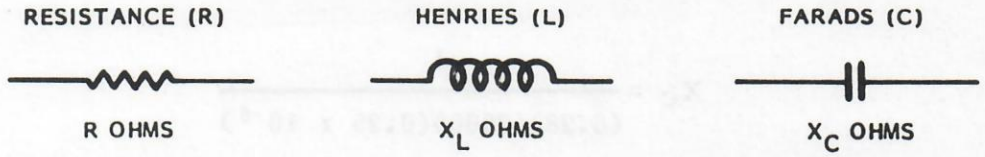


Figure 1 - Components that oppose the flow of ac.

The larger the plate area of a capacitor, the longer it takes to charge or discharge in reaction to a source voltage change and so the longer the period of current flow. This results in a higher average circuit current flow and so the conclusion is that the larger the capacitance value, the greater the current flow for a given frequency. This means that X_C reduces as a C increases, an inverse relationship.

The capacitive reactance also varies with the frequency of the applied voltage. As the frequency and rate of voltage change increase, the capacitor can reach peak charge more easily and the average circuit current increases. An increasing current as the frequency rises means the reactance decreases, also an inverse relationship.

The equation used to determine capacitive reactance is:

CAPACITIVE REACTANCE	$X_C = \frac{1}{2\pi fC}$

where X_C = capacitive reactance in ohms
$2\pi = 6.28$
f = frequency in hertz
C = capacitance in farads

The inverse relationship of X_C to f and C means that as frequency and or capacitance are increased, X_C will decrease.

For example, a 0.25 μF capacitor at 2,000 hertz will offer a reactance to the flow of current of:

$$X_C = \frac{1}{2\pi fC}$$

Before substituting, C in microfarads must be converted to farads by multiplying C by 10^{-6}. Thus:

$$X_C = \frac{1}{(6.28)(2000)(0.25 \times 10^{-6})}$$

$$= \frac{10^6}{(6.28)(2000)(0.25)}$$

$$= \frac{10^6}{3140}$$

X_C AT 2000 Hz FOR 0.25 μF	X_C = 318.5 OHMS

The same capacitor, 0.25 μF, will have a higher reactance if the frequency is lowered. For example, at 1,000 hertz, the capacitive reactance of the 0.25 μF capacitor is:

$$X_C = \frac{1}{(6.28)(1000)(0.25 \times 10^{-6})}$$

$$= \frac{10^6}{(6.28)(1000)(0.25)}$$

$$= \frac{10^6}{1570}$$

X_C AT 1000 Hz FOR 0.25 μF	X_C = 637 OHMS

The relationship between X_C and frequency is shown in Figure 2. From the curve in Figure 2, it can be seen that at low frequencies X_C is high and that as the frequency is increased, X_C drops. Note that the curve is non-linear as it is a plot of an inverse or reciprocal action.

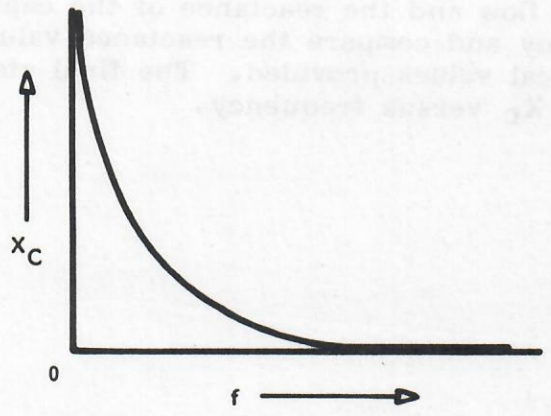


Figure 2 - X_C versus frequency for a given value of C.

Because X_C varies with frequency, a series RC voltage divider circuit will produce a varying output for a varying frequency input. This is illustrated in Figure 3 where it is shown that the output voltage is high at the lower frequencies when X_C is high and reduces as the frequency increases (and X_C decreases).

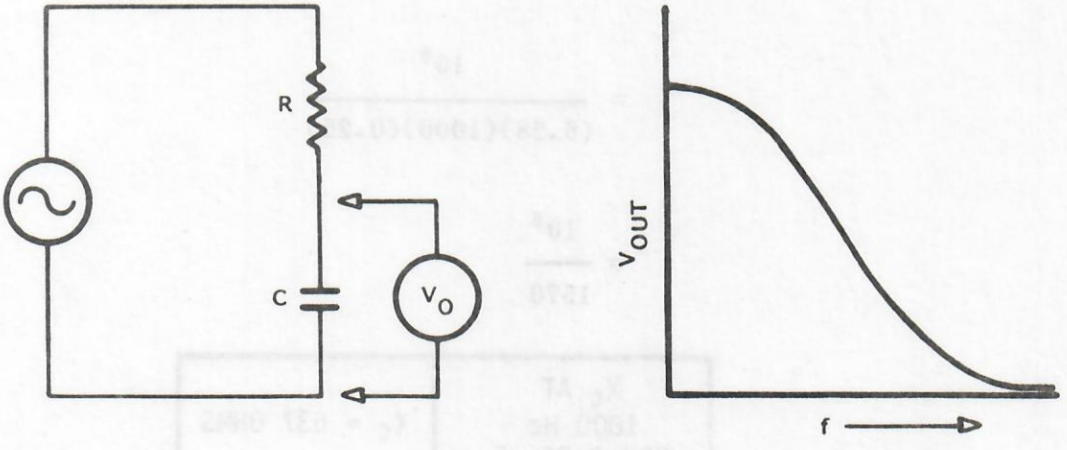


Figure 3 - Plot of output voltage versus frequency for an RC voltage divider.

In this experiment, you will wire an RC voltage divider circuit across the sine wave output of the Function Generator and vary the frequency over a range of 200 Hz to 4 kHz. For each frequency, you will measure the voltage drops across R and C. You will then calculate the circuit current flow and the reactance of the capacitor at each frequency and compare the reactance values to the theoretical values provided. The final steps are to plot V_O and X_C versus frequency.

PROCEDURE

1. Wire the series RC circuit shown in Figure 4.

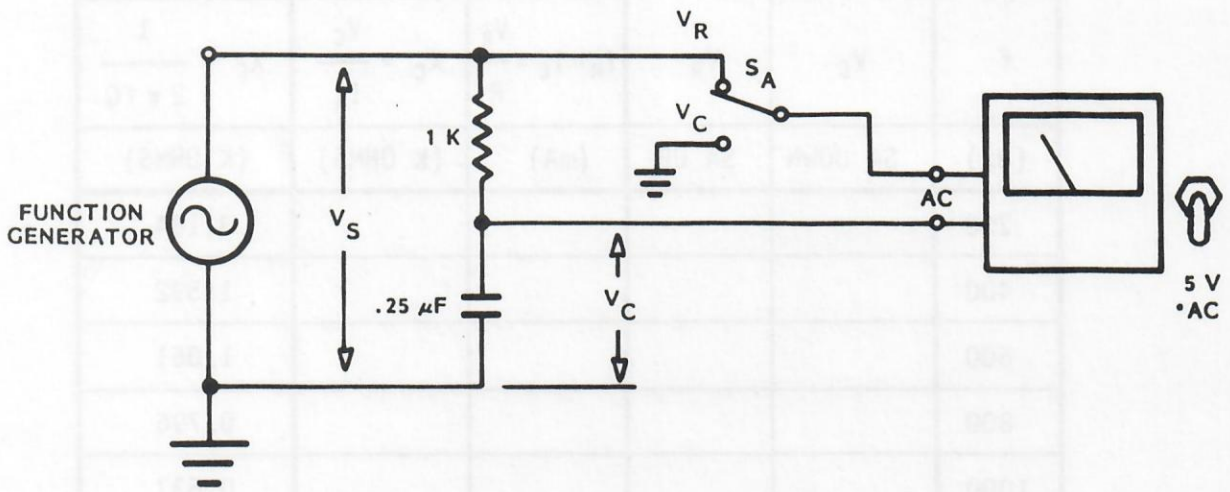


Figure 4 - Capacitive voltage divider EXPERIMENT.

2.1 VOLTAGE MEASUREMENT

2. Adjust the Function Generator to 200 Hz on the 100 to 1 K range.

   Set the SINE AMPL. control to maximum output.

3. With the Function Generator at 200 Hz, place Switch SA DOWN to measure the voltage across the capacitor, V_C, and record it in Table 1, column 2.

   Move Switch SA UP to measure the voltage across the resistance, V_R, and record it in Table 1, column 3.

SET	MEASURE		CALCULATE		COMPARE
1	2	3	4	5	6
f	V_C	V_R	$I_R = I_C = \frac{V_R}{R}$	$X_C = \frac{V_C}{I_R}$	$X_C = \frac{1}{2\pi fC}$
(Hz)	SA DOWN	SA UP	(mA)	(K OHMS)	(K OHMS)
200					3.184
400					1.592
600					1.061
800					0.796
1000					0.637
1500					0.425
2000					0.318
2500					0.254
3000					0.212
3500					0.181
4000					0.159

TABLE 1 - Data for the RC network of Figure 4.

4. Repeat the voltage measurement of V_C and V_R for each frequency listed in column 1 of Table 1 and enter the readings in columns 2 and 3.

2.2 CALCULATING X_C

5. Using the data from Table 1 calculate I_R for each frequency from:

$$I_R = \frac{V_R}{R} \quad \text{where R = 1000 ohms}$$

Because R is 1 K, the answer to each computation will be in milliamperes, exactly equal to the resistor voltage drop. For example, a voltage drop of 1.1 volts will equal 1.1 mA.

$$I_R = \frac{V_R}{R} = \frac{1.1}{1\ K} = 1.1\ mA$$

Enter the current value, I_R, for each frequency in column 4 by copying the number from column 3 in Table 1.

6. Because R and C are in series, I_R is equal to I_C. With both I_C and V_C known, X_C may be calculated from the ac version of Ohm's Law.

$$\text{Ohm's Law} \quad R = \frac{E}{I}$$

$$\text{becomes} \quad X_C = \frac{V_C}{I_C}$$

Calculate X_C for each frequency and enter the results in column 5 of Table 1. Remember, if I_C is entered in mA, the resistance is read in K.

2.3 THEORETICAL X_C

7. The theoretical values of X_C have already been calculated from

$$X_C = \frac{1}{2\pi fC}$$

and the results entered in column 6 of Table 1.

Compare the measured and theoretical values of X_C in columns 5 and 6.

Are the theoretical reactance values in column 6 close to the measured reactance values?

To what do you attribute any differences between the calculated and theoretical reactance values?

2.4 OUTPUT VOLTAGE–RESPONSE PLOT

8. Plot the output voltage, V_O, same as V_C, of the circuit of Figure 4 (from the data in Table 1), as a function of frequency on the graph shown in Figure 5. Observe how the output voltage varies with frequency as X_C changes. This is a plot of an inverse or reciprocal function.

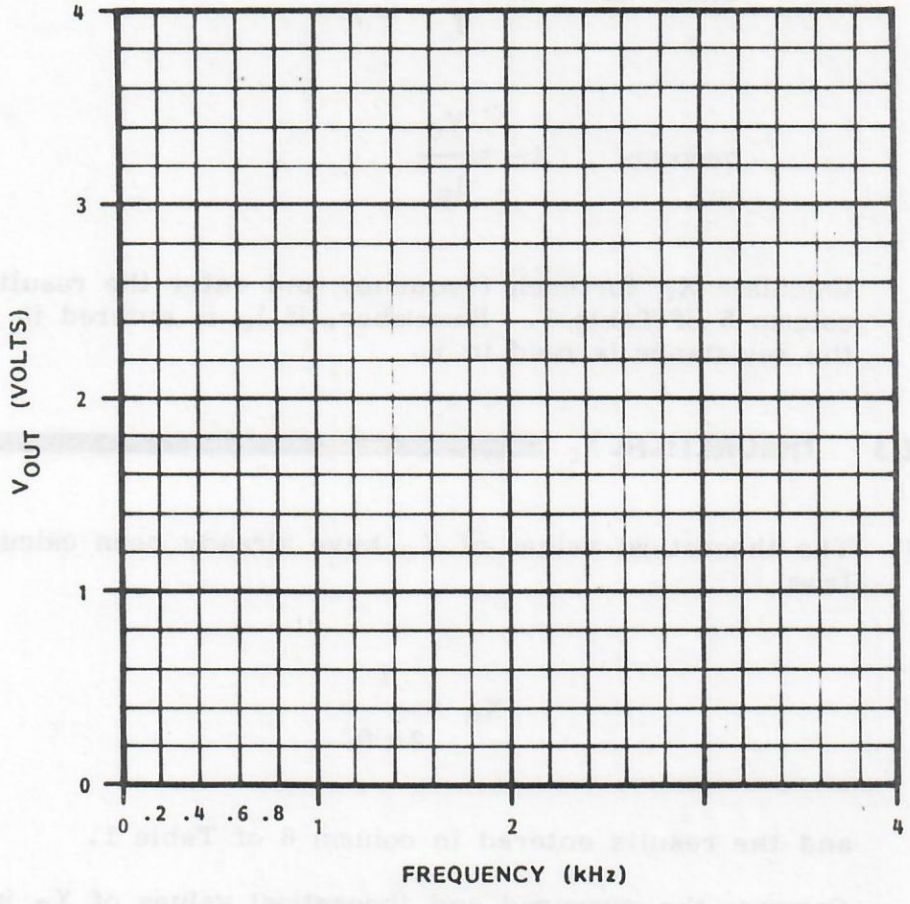


Figure 5 - Output voltage versus frequency.

2.5 PLOTTING X_C VERSUS FREQUENCY

9. Plot the theoretical reactance points (column 6 of Table 1) on the graph in Figure 6. Circle each plot point.

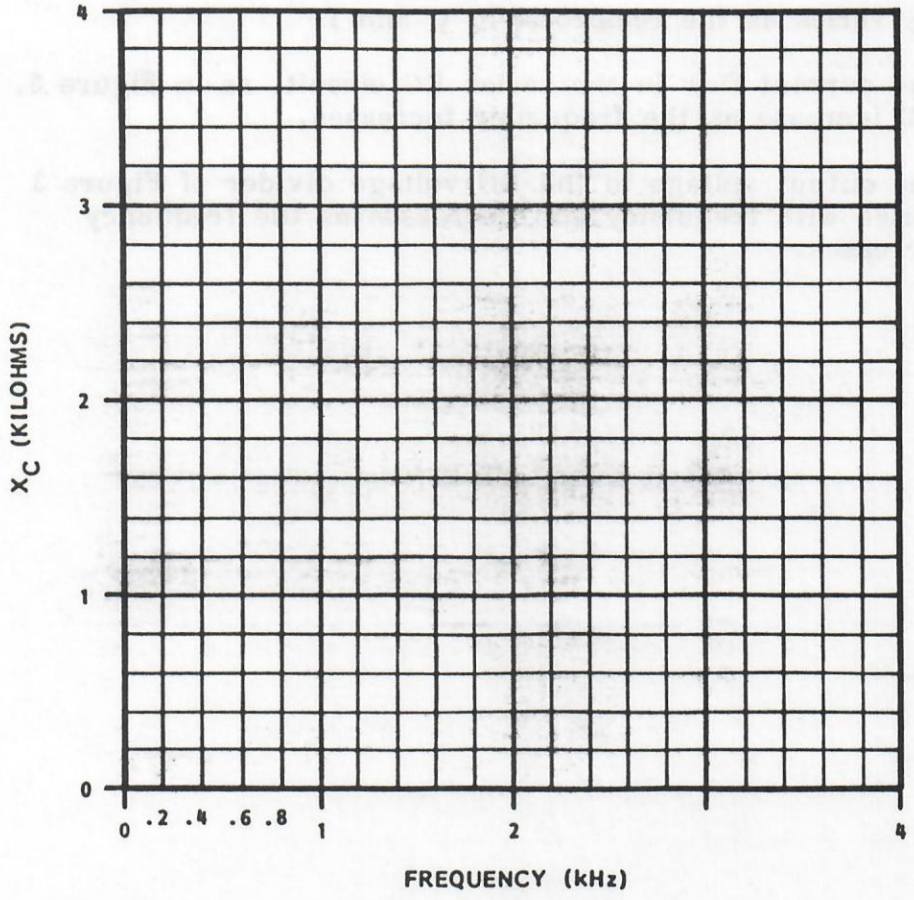


Figure 6 - Plot of theoretical and actual reactance versus frequency.

10. Plot the measured values of X_C (column 5 of Table 1) on the graph in Figure 6. Draw a "triangle" around each plot point. Draw a best fit curve connecting the points.

How do the measured and theoretical reactance points compare?

_____

_____

_____

CONCLUSIONS

We have learned from this experiment that:

X_C decreases as frequency increases.

X_C varies as the reciprocal of C and f.

The current flow in the series RC circuit, as in Figure 3, will increase as the frequency increases.

The output voltage in the RC voltage divider of Figure 3 varies with frequency and decreases as the frequency increases.

ASSIGNMENT

Answer the following True-False questions.

1. The reactance of a capacitor varies inversely with frequency. _____

2. The plot of reactance versus frequency results in a straight line because X_C has a reciprocal relationship to f. _____

3. Capacitive reactance can be defined as the opposition of a capacitor to the flow of alternating current in the circuit. _____

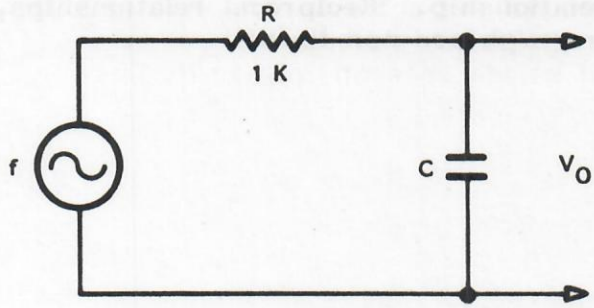


Figure 7 above refers to questions 4 to 7.

4. In the circuit of Figure 7, when f is increased V_O will drop in value. _____

5. If, in Figure 7, V_R equals 1.2 volts and V_C equals 2.4 volts, the reactance of C is equal to 2000 ohms. _____

6. As the capacitance of a capacitor in Figure 7 is increased X_C also increases given that f remains the same. _____

7. If, in Figure 7, the frequency is 5 kHz and the capacitor is 0.05 μF, the capacitive reactance is 637 ohms. _____

KEY TERMS

1. CAPACITIVE REACTANCE (X_C)

   The opposition to the flow of alternating current through a capacitor. It is measured in ohms, indicated as X_C and calculated from

$$X_C = \frac{1}{2\pi fC}$$

2. REACTANCE (X)

   Opposition to the flow of alternating current. Reactance is measured in ohms and indicated as X.

3. RECIPROCAL

   The reciprocal of a number is 1 divided by that number. The formula for capacitive reactance above is a reciprocal relationship. Reciprocal relationships, when plotted on a graph are non-linear.

AC Voltages and Phasors

INFO SHEET 1

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Perform right triangle calculations.
2. Describe phasor construction.
3. Construct a phasor for out-of-phase voltages.
4. Explain the phase shift that occurs in L and C circuits.
5. Calculate voltage drops in series reactive circuits.
6. Calculate the impedance of series reactive circuits.
7. Calculate phase angles in series reactive circuits.

DISCUSSION

In the previous experiments, the ac voltages in series RL and RC circuits were used to calculate capacitive and inductive reactance, the equivalent of "ac resistance." It was shown that these are equal to:

CAPACITIVE

$$X_C = \frac{1}{2\pi fC}$$

INDUCTIVE

$$X_L = 2\pi fL$$

In the experiments that follow, you will add the circuit voltages, calculate and measure IMPEDANCE which is the total of the circuit Resistance and Reactance.

The first experiment following this information sheet involves the measurement of voltages in a series RC circuit. A simple series RC circuit is shown in Figure 1 together with typical ac voltages that might result from measurement with an rms ac meter.

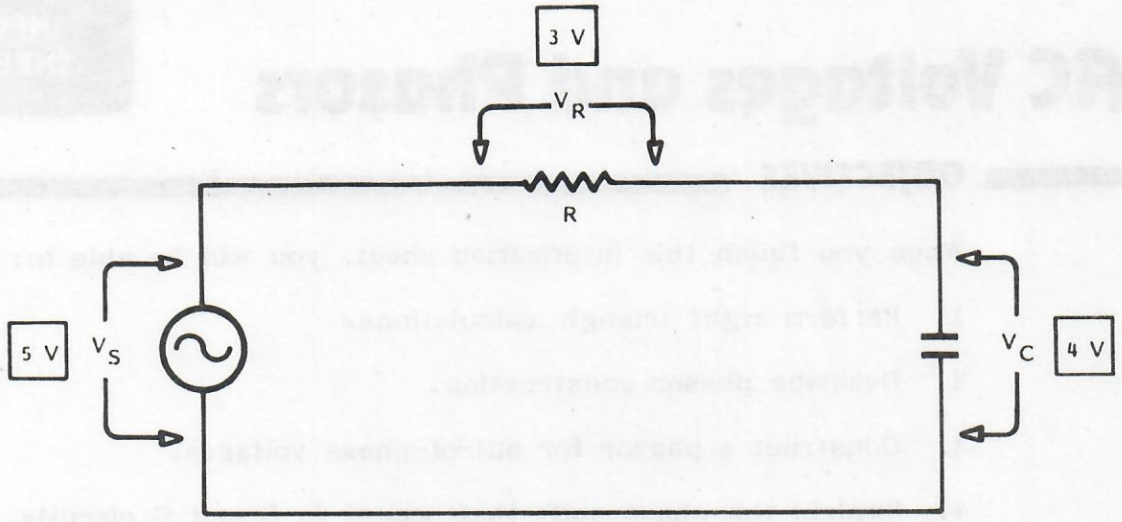


Figure 1 - Series RC circuit and voltage distribution.

Kirchhoff's Voltage Law applies to ac circuits as well as dc circuits but if you add $V_R + V_C$ directly in Figure 1, you obtain 3 + 4 or 7 volts which does not equal the applied voltage, V_S, of 5 volts.

INSTANTANEOUS ADDITION

In ac circuits, you cannot add the voltages directly if the voltages are not in PHASE, that is, if they do not both reach their peak at the same time. If the two voltages are OUT OF PHASE, as shown in Figure 2, they can only be added directly using the "instantaneous" voltages as shown. Figure 2 shows two voltages 90° apart with voltage A appearing first and voltage B reaching peak 90° later as would occur in an RC circuit. The voltages, each 1 volt peak, do not add to 2 volts peak but to 1.414 volts as shown in waveform C because the two peaks occur 90° apart.

PHASORS, VECTORS AND TRIANGLES

To make it possible to add ac voltages or currents that are not in phase, that is, that do not start (zero) or reach the peak at the same time, as in Figure 2, you would use VECTOR diagrams, more commonly called PHASOR diagrams in electronics. You would not add the instantaneous values as in Figure 2 because it is too lengthy a method.

Phasor diagrams involve the use of some basic and elementary geometry and trigonometry. First, there is the RIGHT TRIANGLE and then there are the basic trigonometric relationships in that triangle.

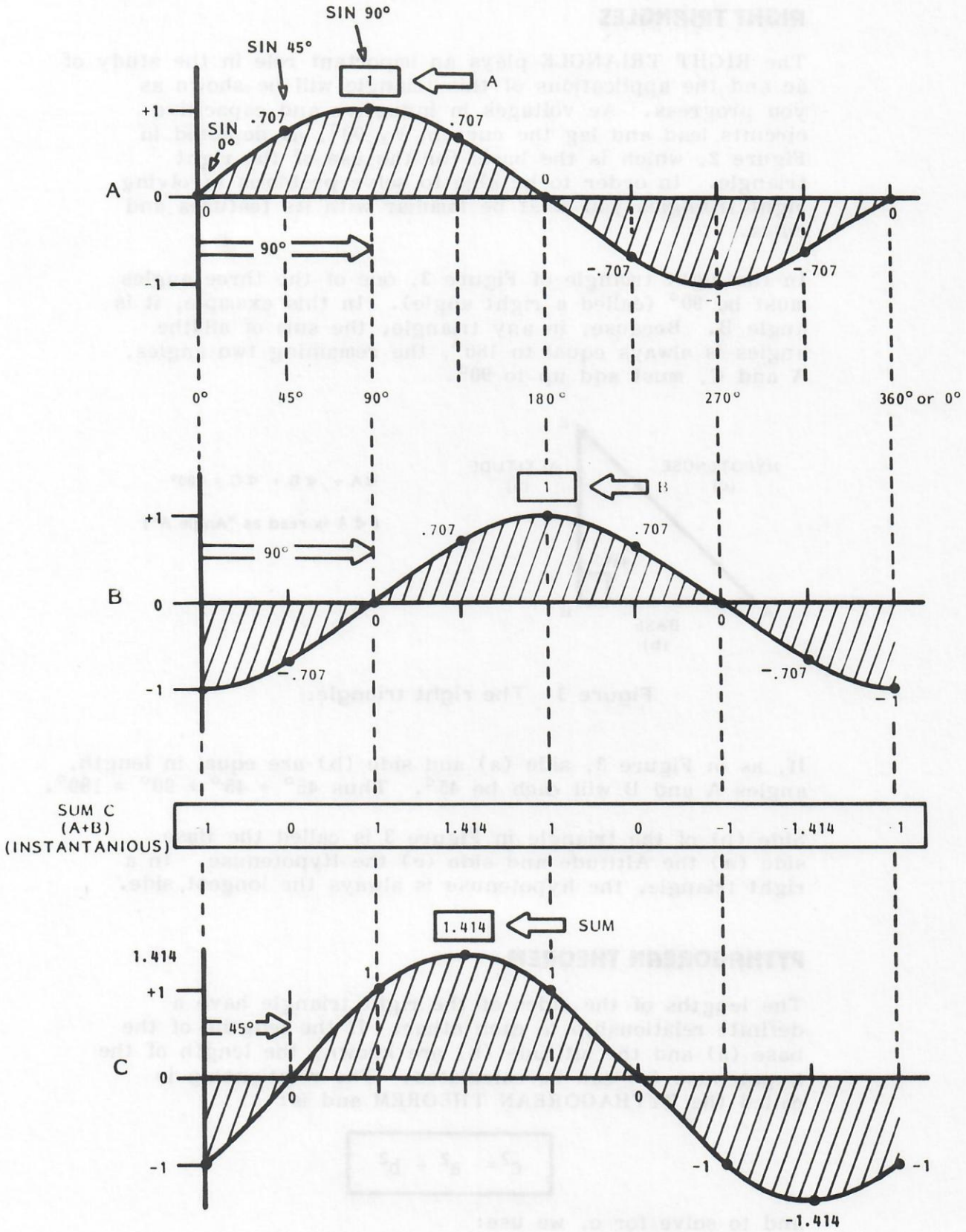
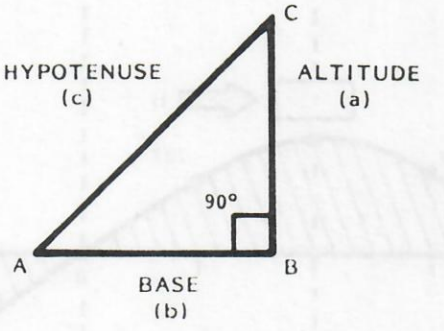


Figure 2 - Instantaneous addition of two ac voltages.

RIGHT TRIANGLES

The RIGHT TRIANGLE plays an important role in the study of ac and the applications of this triangle will be shown as you progress. Ac voltages in inductive and capacitive circuits lead and lag the current by 90°, as depicted in Figure 2, which is the basis for the use of the right triangle. In order to be able to solve problems involving right triangles you must be familiar with its features and rules.

In the right triangle of Figure 3, one of the three angles must be 90° (called a right angle). In this example, it is angle B. Because, in any triangle, the sum of all the angles is always equal to 180°, the remaining two angles, A and C, must add up to 90°.



∢A + ∢B + ∢C = 180°

(∢A is read as "Angle A")

Figure 3 - The right triangle.

If, as in Figure 3, side (a) and side (b) are equal in length, angles A and B will each be 45°. Thus 45° + 45° + 90° = 180°.

Side (b) of the triangle in Figure 3 is called the Base, side (a) the Altitude and side (c) the Hypotenuse. In a right triangle, the hypotenuse is always the longest side.

PYTHAGOREAN THEOREM

The lengths of the sides of the right triangle have a definite relationship to each other. If the lengths of the base (a) and the altitude (b) are known, the length of the hypotenuse (c) can be calculated. The relationship is called the PYTHAGOREAN THEOREM and is:

$$c^2 = a^2 + b^2$$

and to solve for c, we use:

$$c = \sqrt{a^2 + b^2}$$

To determine the hypotenuse of the right triangle shown in Figure 4(a) when side a = 3 and side b = 4, we have:

$$c = \sqrt{a^2 + b^2}$$

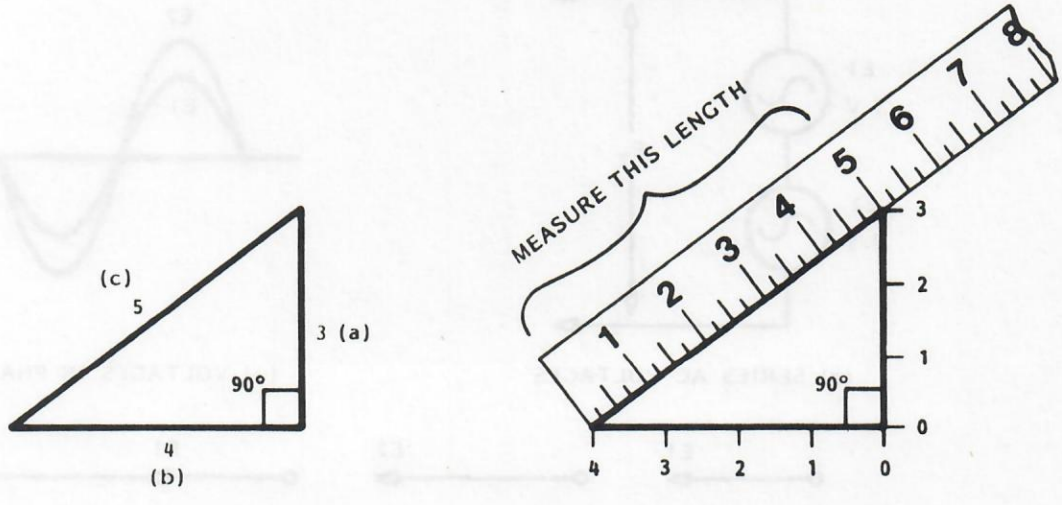
$$= \sqrt{3^2 + 4^2}$$

$$= \sqrt{9 + 16}$$

$$= \sqrt{25}$$

HYPOTENUSE	c = 5

It is also possible to solve for the hypotenuse graphically, that is, actually draw the right angle on paper and measure the length of the hypotenuse as shown in Figure 4 (b).



(a) RIGHT TRIANGLE (b) GRAPHIC PLOT

Figure 4 - The 3-4-5 right triangle and its graphic solution.

The illustration used in Figure 4 is called the "3-4-5" triangle and, because it works out evenly, is used to illustrate many examples as you will see in this information sheet and the experiments that follow.

PHASOR DIAGRAMS

PHASE means the comparitive "time" of occurrence between two or more actions or events. It is the time interval between the instants when the first and second events take place. In ac circuits, the voltages and currents change continuously and so the concept of phase is important when the timing of two or more ac voltages or currents are to be compared. The time difference is the time between peaks which will be the same as the time between zero crossovers. When measuring the phase or time difference between two ac waveforms, the unit of measurement is degrees because a single sine wave is marked off in 360 degrees. This was illustrated in Figure 2.

If two ac voltages are wired in series, as shown in Figure 5(a), the total voltage, E_T, is not only dependent upon the individual voltage values but their timing or "phase" as well. This is further illustrated in Figure 5(b) where we have an example with both voltages beginning and ending their cycles together and both going positive together. The two voltages have no time difference and are said to be IN PHASE and add directly as illustrated by the phasors in Figure 5(c) (d) and (e).

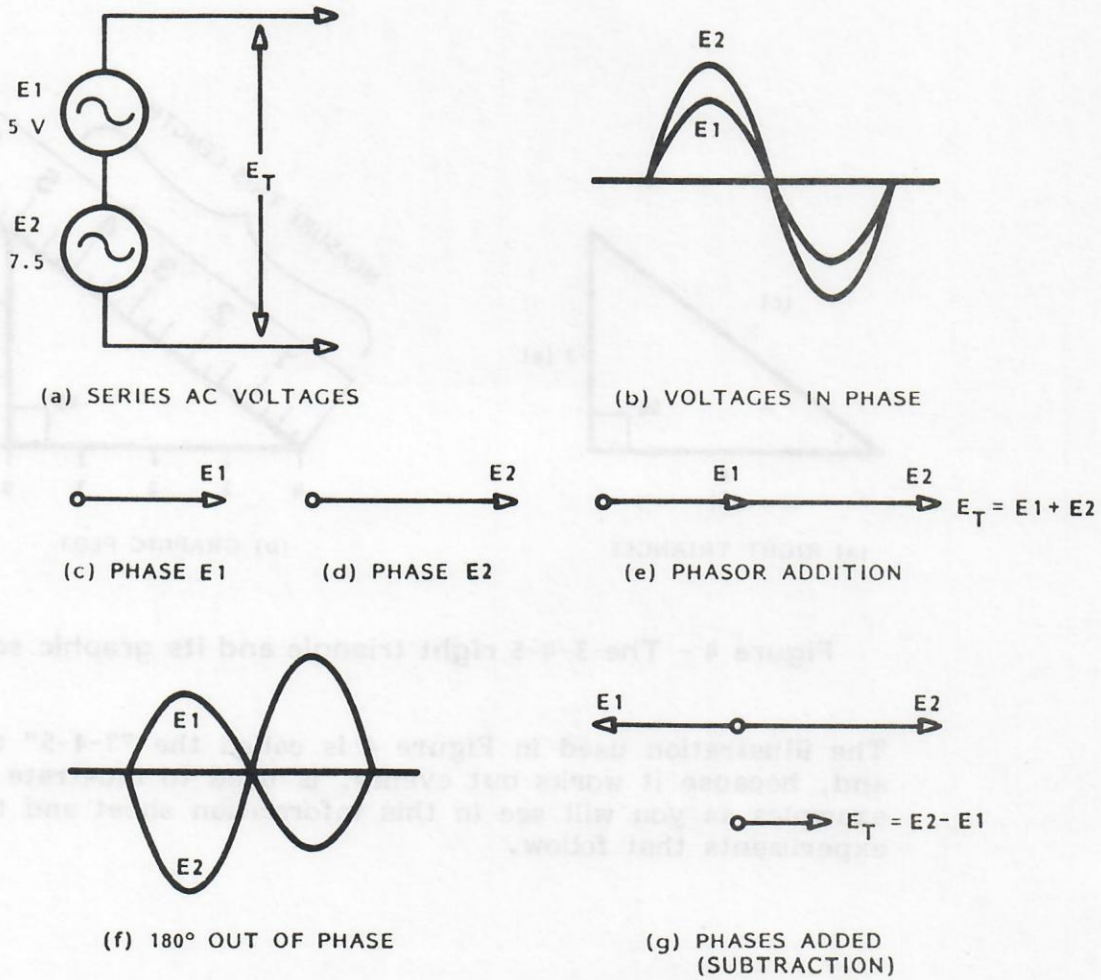
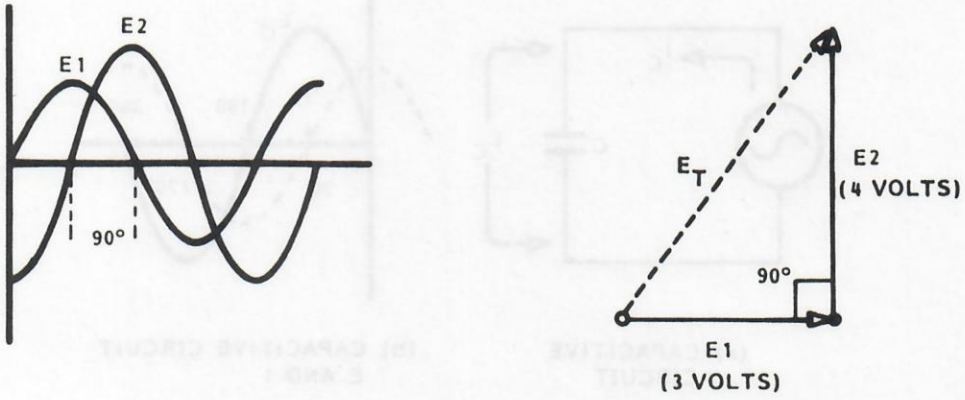


Figure 5 - Phase relationships of two ac voltages.

When voltages E1 and E2 are 180° OUT OF PHASE they appear as shown in Figure 5(f). When E1 reaches it maximum positive peak, E2 reaches its maximum negative peak. As shown in (g), the phasors are drawn in opposite directions, 180° apart and they cancel. The resultant, E_T, is the difference voltage.

OUT OF PHASE BY 90 DEGREES

It is also possible to plot two voltages that are not in phase and not 180° out of phase but somewhere in between. For example, if two voltages are 90° out of phase, as is very common in electronics, they are as shown in Figure 6(a) and plotted by phasors as in 6(b). Note that the phasors form a right triangle and E2 leads E1 by 90°.



(a) VOLTAGES 90° OUT OF PHASE

(b) 90° PHASOR

Figure 6 - Voltages 90° out of phase.

Since the voltages in Figure 6(a) are neither in phase nor 180° out of phase, they do not add or cancel directly. If the two voltages are exactly 90° apart, as shown, they can be added using phasors as in Figure 6(b) above or they may be added using the Pythagorean Theorem as shown below.

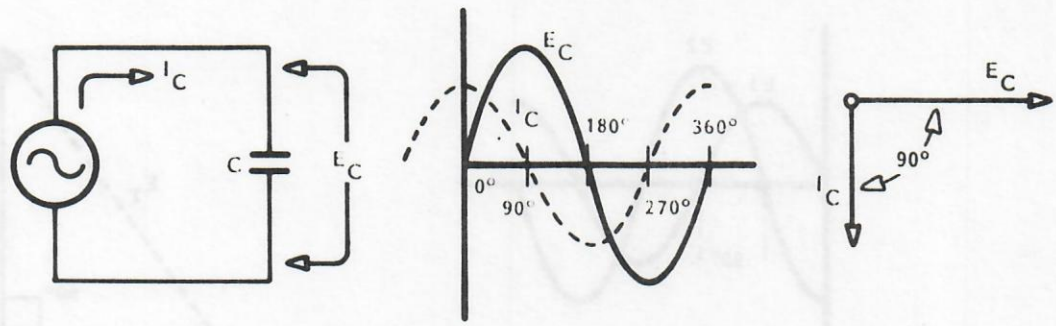
$$E_T = \sqrt{E_1^2 + E_2^2} = \sqrt{3^2 + 4^2}$$

$$= \sqrt{9 + 16} = \sqrt{25}$$

$$E_T = 5 \text{ VOLTS}$$

CAPACITIVE PHASE SHIFT

When a capacitor is connected across an ac sine wave voltage source, a sine wave current will flow in the circuit as the capacitor charges and discharges. The current flow in the capacitor circuit is at maximum when the rate of change (roc) or the slope of the voltage is the greatest and the maximum rate of change of voltage occurs when the voltage sine waveform is going through zero. Thus, the capacitor charging current, I_C, reaches its peak value 90° BEFORE the voltage, E_C, reaches its peak value as shown in Figure 7(b). This condition of current leading voltage by 90° in a capacitor is demonstrated in an experiment. The phasor representation of the waveforms in Figure 7(b) is shown in Figure 7(c).



(a) CAPACITIVE CIRCUIT

(b) CAPACITIVE CIRCUIT E AND I

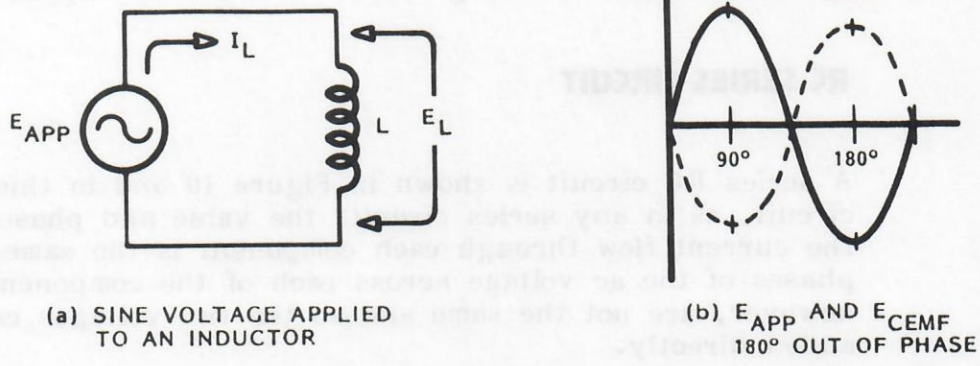
(c) PHASOR DIAGRAM

Figure 7 - Phase relationship of E and I in a capacitor.

Figure 7(b) shows that I leads E by 90° in a capacitor. This can be understood from our earlier understanding of capacitor operation. When a capacitor is connected across a dc voltage source, there is an immediate current flow. (An uncharged capacitor is like a momentary short circuit, that is, it has zero voltage across it and maximum current.) The voltage across the capacitor, however, builds slowly and the current decreases slowly so that current leads the voltage in the capacitive circuit. At the starting time, the current applied is at maximum and the capacitor voltage is at zero. When the capacitor voltage reaches the maximum, the current becomes zero.

INDUCTIVE PHASE SHIFT

Earlier, in Unit F - Magnetism, you learned that when a varying current flows through an inductor, a counter electromotive force (cemf) that opposes the applied voltage, is generated. If a sine waveform is applied to the inductor as in Figure 8(a), the applied voltage (E_{APP}) and the counter emf voltage (E_{CEMF}), will appear 180° out of phase as in Figure 8(b).

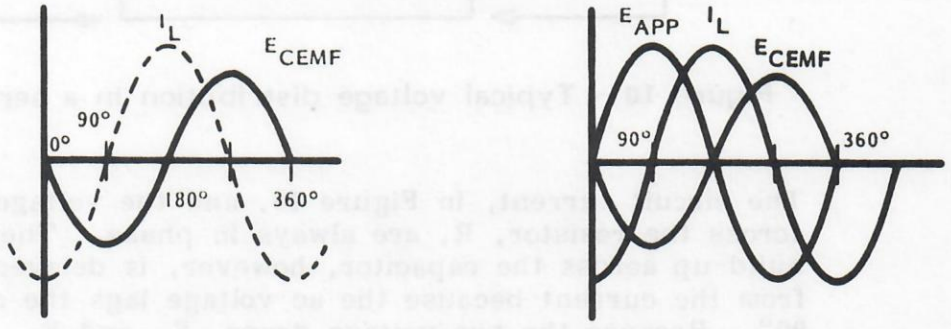


(a) SINE VOLTAGE APPLIED TO AN INDUCTOR

(b) E_{APP} AND E_{CEMF} 180° OUT OF PHASE

Figure 8 - Inductor phase relationship between E_{APP} and E_{CEMF}.

The sine wave of current flowing through the inductor is 90° out of phase with the counter emf. This is so because the cemf can be maximum only when the current rate of change (slope) is maximum. This happens when the current goes through zero. This is shown in Figure 9(a) to be at 90° and 270° points.



(a) I LEADS E_{CEMF} BY 90°

(b) I LAGS E_{APP} BY 90°

Figure 9 - Inductive phase relationship between E and I.

The counter emf in Figure 9(a) is at zero at three points, 0°, 180°, and 360°. This occurs because the current, I_L, is at its peaks (negative and positive) where it has stopped rising and has not yet started to fall. At these points, the current is momentarily constant and no counter emf is induced resulting in a zero counter emf.

By adding the applied voltage from Figure 8(a) to the graph in 9(b), the current I_L, may now be compared to the applied voltage, E_{APP}. It can be seen that the current is DELAYED by 90° or that the voltage LEADS the current by 90°.

RC SERIES CIRCUIT

A series RC circuit is shown in Figure 10 and in this circuit, as in any series circuit, the value and phase of the current flow through each component is the same. The phases of the ac voltage across each of the components, however, are not the same and so the two voltages cannot be added directly.

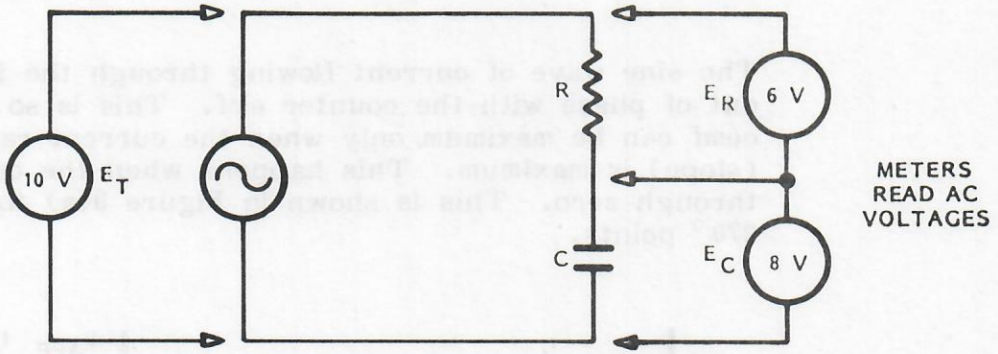
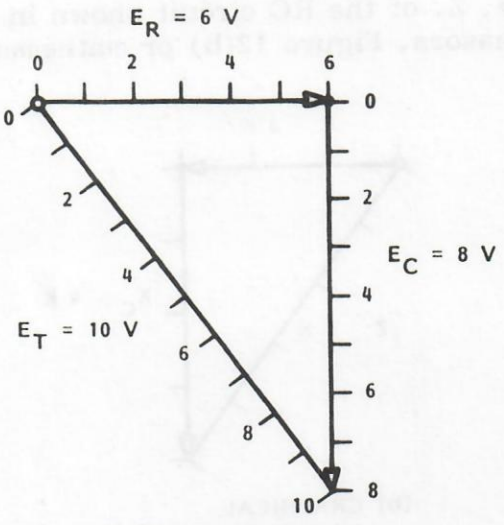


Figure 10 - Typical voltage distribution in a series RC circuit.

The circuit current, in Figure 10, and the voltage drop across the resistor, R, are always in phase. The voltage build-up across the capacitor, however, is delayed by 90° from the current because the ac voltage lags the current by 90°. Because the two voltage drops, E_R and E_C, are out of phase, the total voltage cannot be determined by direct addition of the rms ac voltage drops. Obviously, the numerical sum of 6 plus 8 does not equal the source voltage of 10 volts. The correct total voltage can be determined by constructing a phasor as shown in Figure 11(a) or applying the Pythagorean Theorem as shown in Figure 11(b).



(a) RIGHT TRIANGLE GRAPHIC SOLUTION

$$E_T = \sqrt{E_R^2 + E_C^2}$$

$$= \sqrt{6^2 + 8^2}$$

$$= \sqrt{36 + 64}$$

$$= \sqrt{100}$$

$$\boxed{E_T = 10 \text{ VOLTS}}$$

(b) ALGEBRAIC SOLUTION

Figure 11 - Methods of adding two voltages 90° out of phase.

Figure 11(a) illustrates the solution by the construction of the right triangle and drawing and measuring the hypotenuse. A construction such as this is time consuming, not always precise, and requires special materials such as graph paper, straight edge and, occasionally, a protractor for measuring angles. The use of the Pythagorean Theorem in Figure 11(b) is more accepted and not difficult as long as a calculator is used.

RC IMPEDANCE (Z)

In a series resistive circuit it was shown that:

$$R_T = R1 + R2 + R3 + \text{-------} \quad R_n$$

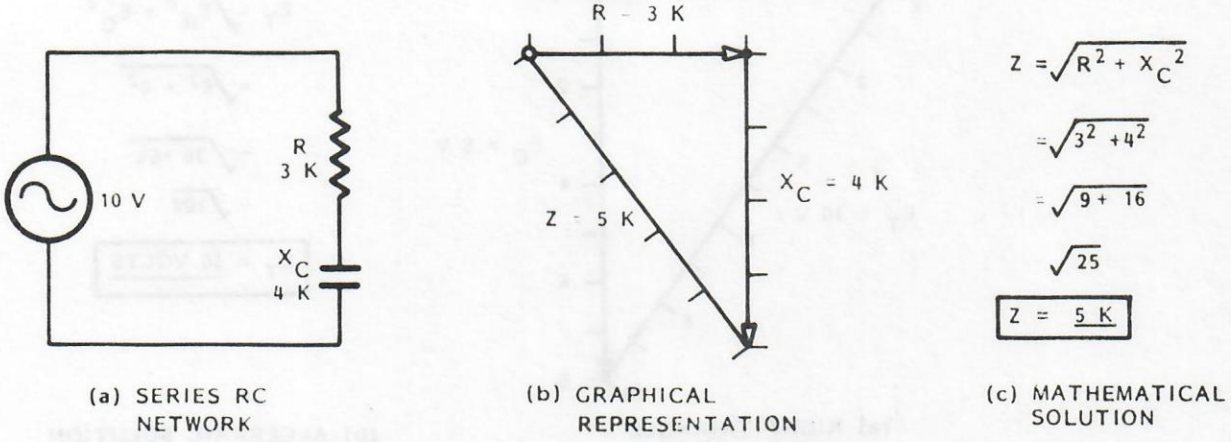
In a series capacitive circuit the reactances are also directly additive. Thus:

$$X_{CT} = X_{C1} + X_{C2} + X_{C3} + \text{--------} \quad X_{Cn}$$

In a series RC circuit, such as shown in Figure 10, the resistance and reactance cannot be added directly.

The combination of R and X_C is called IMPEDANCE, written as Z and also measured in ohms. The impedance of a series RC circuit is its total opposition to the flow of ac current. It can be calculated using the right triangle or by formula just as the voltage drops in the RC circuit were added together.

The total impedance, Z, of the RC circuit shown in Figure 12(a) is determined by phasors, Figure 12(b) or mathematically as in Figure 12(c).



(a) SERIES RC NETWORK

(b) GRAPHICAL REPRESENTATION

(c) MATHEMATICAL SOLUTION

Figure 12 - The Impedance Triangle and solution.

As shown in Figure 12, the impedance, Z, of a series RC circuit containing a 3 K resistance and a 4 K capacitive reactance is not 7 K, the simple sum, but 5 K. The solution is shown by the right triangle construction (the 3-4-5 triangle) and is easily calculated by the Pythagorean Theorem in Figure 12(c).

RC CURRENT FLOW

The current flow in the RC circuit of Figure 12(a) is governed by ac Ohm's Law where:

$$I = \frac{E}{Z}$$

For example, given the 3 K resistance in series with capacitor whose reactance is 4 K and connected across a 10 volt ac source, the circuit current flow is calculated as shown below.

It was shown that for a 3 K resistance and a 4 K reactance that Z = 5 K. Thus:

$$I = \frac{E}{Z}$$

$$= \frac{10}{5K}$$

$$\boxed{I = 2 \text{ mA}}$$

RC PHASE ANGLES (THETA or θ)

The voltage phasor and impedance phasor, for the simple series RC network of Figure 10, were given earlier in Figures 11(a) and 12(b). These phasors are shown again in Figure 13(a) and (b).

Observe, in Figure 13, that the current, I_T, is added to the phasor diagram. Since I_T is in phase with V_R, it is shown on the same base line. Observe further, in Figure 13, that the applied voltage or total source voltage, V_T, and the total current (I_T) are out of phase. The current is leading the voltage by some numer of degrees as shown by the Greek letter theta, θ. The number of degrees by which the current leads the source voltage, V_T, is called the PHASE ANGLE and is labeled θ.

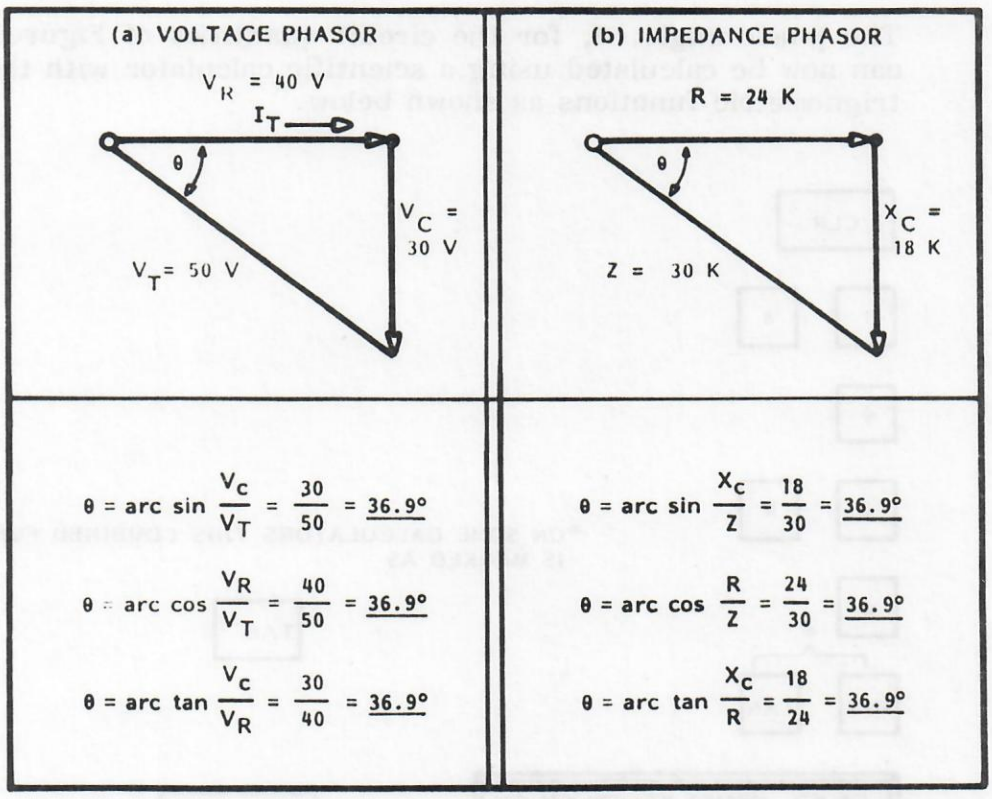

(a) VOLTAGE PHASOR
V_R = 40 V
I_T
θ
V_C = 30 V
V_T = 50 V
(b) IMPEDANCE PHASOR
R = 24 K
θ
X_C = 18 K
Z = 30 K
$\theta = \text{arc sin } \frac{V_C}{V_T} = \frac{30}{50} = 36.9°$
$\theta = \text{arc cos } \frac{V_R}{V_T} = \frac{40}{50} = 36.9°$
$\theta = \text{arc tan } \frac{V_C}{V_R} = \frac{30}{40} = 36.9°$
$\theta = \text{arc sin } \frac{X_C}{Z} = \frac{18}{30} = 36.9°$
$\theta = \text{arc cos } \frac{R}{Z} = \frac{24}{30} = 36.9°$
$\theta = \text{arc tan } \frac{X_C}{R} = \frac{18}{24} = 36.9°$

Figure 13 - Basic trig functions used to calculate theta.

PHASE ANGLE CALCULATIONS

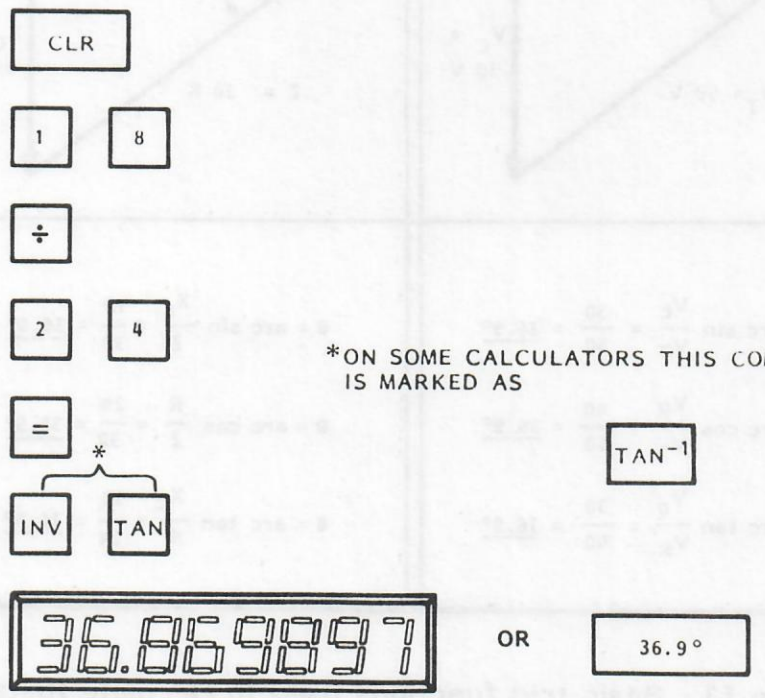
If the phasors in Figure 13 are constructed large enough and with sufficient accuracy, the angle theta can be measured with a protractor. It is simpler, however, and more accurate, to calculate the phase angle using one of the three basic trigonometric functions (sine, cosine, tangent) given in Figure 13. The equation used to calculate theta should be the one for which the data are available.

EXAMPLE

Consider the values shown in the impedance phasor of Figure 13(b). If only R and X_C are known, the only suitable equation in Figure 13 that may be used to determine theta, is:

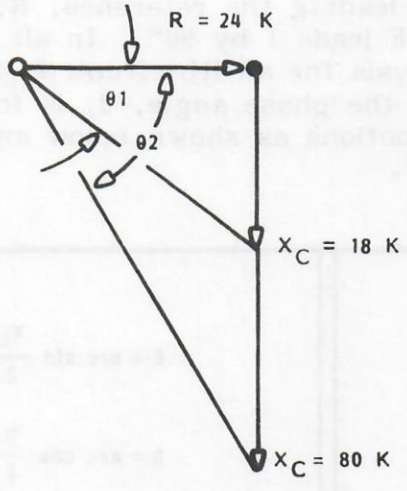
$$\theta = \text{arc tan} \frac{X_C}{R}$$

The phase angle, θ, for the circuit quantities of Figure 13(b) can now be calculated using a scientific calculator with the trignometric functions as shown below.



*ON SOME CALCULATORS THIS COMBINED FUNCTION IS MARKED AS

If, in the simple series RC circuit represented by the phasors of Figure 13(a) and (b), the frequency is decreased, X_C must increase. A change in X_C must change the phase angle, θ, as shown in Figure 14. As X_C increases from 18 K to 80 K, the angle θ will increase, approaching 90°, the theoretical maximum value when only X_C is present in the circuit.



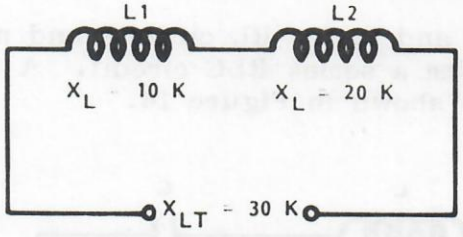
$$\theta 1 = \text{arc tan } \frac{X_C}{R} = \frac{18}{24} = \underline{36.9°}$$

$$\theta 2 = \text{arc tan } \frac{X_C}{R} = \frac{80}{24} = \underline{73.3°}$$

Figure 14 - Phasor diagram showing how θ relates to X_C.

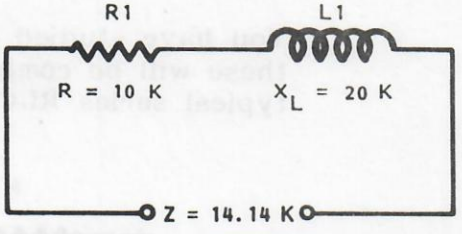
RL SERIES CIRCUITS

In a series inductive circuit, such as shown in Figure 15(a), the reactances are directly additive. Thus, the total reactance is equal to $X_{L1} + X_{L2}$. At a given frequency, when the inductive reactances are 10 K and 20 K, the total inductive reactance is 30 K as shown.



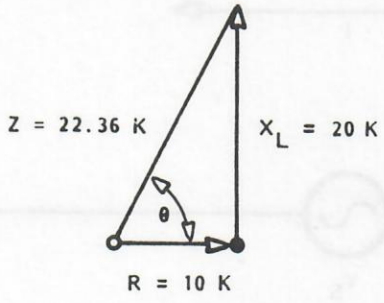
$$X_{LT} = X_{L1} + X_{L2}$$

(a) SERIES INDUCTORS



$$Z = \sqrt{R^2 + X_L^2}$$

(b)SERIES RL CIRCUIT



(c) PHASOR DIAGRAM

$$\theta = \text{arc tan } \frac{X_L}{R}$$

$$\theta = \text{arc tan } \frac{20\text{ K}}{10\text{ K}}$$

$$\theta = \underline{63.43°}$$

(d) PHASE ANGLE CALCULATION

Figure 15 - Series RL circuit and phasor.

When a resistor is wired in series with an inductor, R and X_L cannot be added directly for the same reason explained earlier in RC circuits. The two voltage drops, V_R and V_L, are out of phase. The resistance and inductive reactance can be added using the equation shown in Figure 15(b) and by the phasor shown in Figure 15(c). Note that for an inductor, X_L is shown as leading the reference, R, by 90° because, in an inductor, E leads I by 90°. In all other respects, the phasor analysis for an RL circuit is the same as for the RC circuit and the phase angle, θ, is found using the same trigonometric functions as shown below and calculated in Figure 15(d).

$\theta = \text{arc sin } \frac{V_L}{V_T}$	$\theta = \text{arc sin } \frac{X_L}{Z}$
$\theta = \text{arc cos } \frac{V_R}{V_T}$	$\theta = \text{arc cos } \frac{R}{Z}$
$\theta = \text{arc tan } \frac{V_L}{V_R}$	$\theta = \text{arc tan } \frac{X_L}{R}$

RLC SERIES CIRCUIT

You have studied series RC and series RL circuits and now these will be combined to form a series RLC circuit. A typical series RLC circuit is shown in Figure 16.

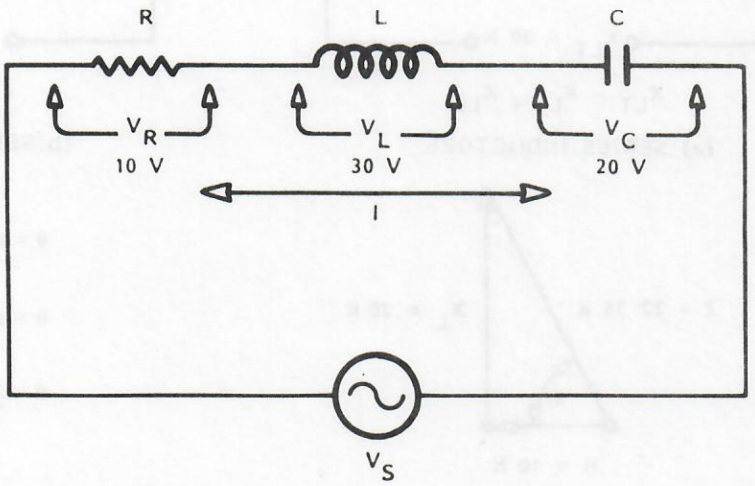


Figure 16 - Typical series RLC network.

As in the previous discussion of RL and RC circuits, the individual voltage drops shown in Figure 16 do not add up to equal the source voltage but will exceed the source voltage. This happens because the individual voltage drops are out of phase with each other. The action of the circuit is best illustrated using phasor diagrams.

RLC PHASOR CONSTRUCTION

As in previous series resistive-reactive circuits, the current, being the same throughout the circuit, is used as the reference direction when defining the circuit voltage phase relationships. Because the voltage drop, V_R, is in phase with the current through the resistance, the reference may be shown as in Figure 17(a) with V_R at the horizontal or zero position.

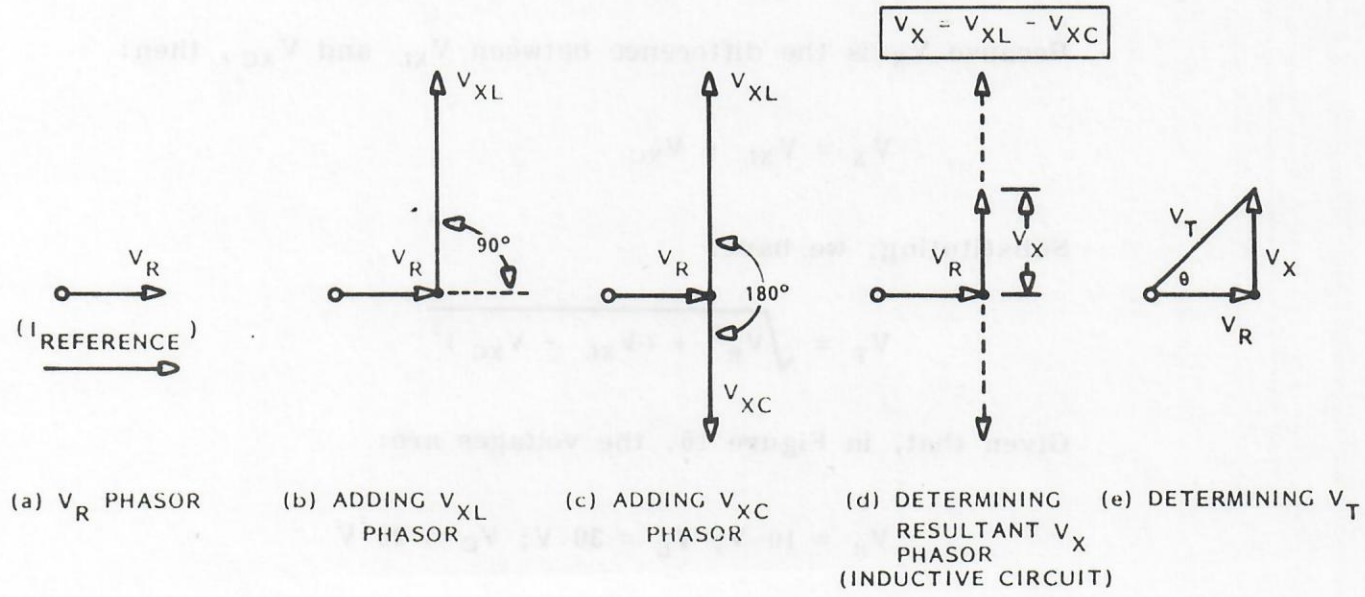


Figure 17 - Construction and solution of a series RLC phasor.

The inductor voltage drop leads the current by 90° so that its phasor arm must be shown upward as in Figure 17(b).

The capacitive voltage drop lags the current by 90° so that its phasor arm must be shown downward as in Figure 17(c). Observe that while V_{XC} lags V_R by 90°, it lags V_{XL} by 180°.

Because V_{XL} and V_{XC} are 180° out of phase, they are to be subtracted from each other. The resultant voltage is the difference between the two. In the phasor diagram of Figure 17(c) it can be seen that V_{XL} is greater than V_{XC} resulting in a net inductive reactive voltage, V_{XL}, or $V_X = V_{XL} - V_{XC}$ as shown in Figure 17(d).

The total voltage, V_T, and the phase angle, θ, may now be determined using the Pythagorean theorem equation for the right triangle or by constructing the phasor and drawing the hypotenuse as shown in Figure 17(e).

RLC TOTAL VOLTAGE

The value of V_T can be determined from the completed vector in Figure 17(e) by measuring the length of the hypotenuse. It is, however, usually more convenient to compute the value of V_T mathematically using the now familiar equation:

$$V_T = \sqrt{V_R^2 + V_X^2}$$

Because V_X is the difference between V_{XL} and V_{XC}, then:

$$V_X = V_{XL} - V_{XC}$$

Substituting, we have:

$$V_T = \sqrt{V_R^2 + (V_{XL} - V_{XC})^2}$$

Given that, in Figure 16, the voltages are:

$$V_R = 10 \text{ V}; \; V_L = 30 \text{ V}; \; V_C = 20 \text{ V}$$

the total voltage, V_T, is:

$$V_T = \sqrt{V_R^2 + (V_{XL} - V_{XC})^2} = \sqrt{10^2 + (30 - 20)^2}$$

$$= \sqrt{100 + 100} = \sqrt{200}$$

RLC CIRCUIT, FIGURE 16	V_T = 14.14 VOLTS

RLC CURRENT AND REACTANCES

The current through the series circuit of Figure 16 can be determined if the voltage drop across one component is known as well as its resistance or reactance. If both V_R and R are known, then:

$$I = \frac{V_R}{R}$$

For Figure 16, with V_R = 10 volts and with R known to be 10 K, the circuit current is:

$$I = \frac{V_R}{R} = \frac{10}{10\ K} = 1\ mA$$

The reactances can now be calculated using the ac version of Ohm's Law.

$$X_C = \frac{V_C}{I_C} = \frac{20}{1\ mA}$$

X_C = 20 K

$$X_L = \frac{V_L}{I_L} = \frac{30}{1\ mA}$$

X_L = 30 K

RLC IMPEDANCE

The impedance of the series RLC circuit can be determined by constructing a phasor similar to that shown in Figure 17 but using resistance and reactance values. This is shown in Figure 18.

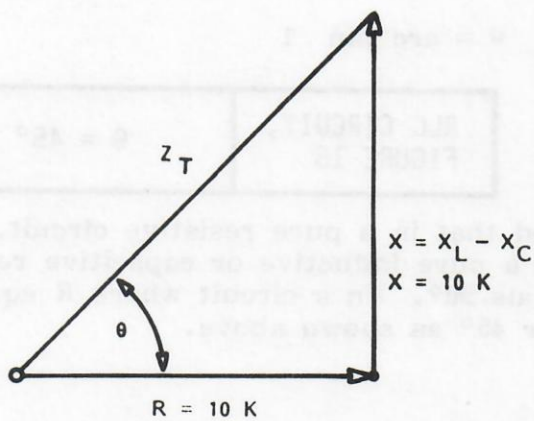


Figure 18 - Solving an RLC circuit for Z_T using an impedance phasor.

Again, as for series RL and RC circuits, Z_T can be calculated from:

$$Z_T = \sqrt{R^2 + X^2}$$

$$= \sqrt{10^2 + (30 - 20)^2}$$

$$= \sqrt{100 + 100} = \sqrt{200}$$

RLC CIRCUIT, FIGURE 16	$Z_T = 14.14$ K

RLC PHASE ANGLE (θ)

The phase angle has been defined earlier as the phase difference between the circuit current and the applied voltage. The phase angle may be calculated using one of three trignometric relationships shown earlier in Figure 13. As shown in Figure 13, theta can be determined from the voltage phasor or the impedance phasor by selecting the most convenient equation based on the available data. Given that, for the circuit of Figure 16, R and X are known, theta is found from:

R = 10 K; X = 10 K

$$\theta = \text{arc tan } \frac{X}{R} = \text{arc tan } \frac{10}{10}$$

$$\theta = \text{arc tan } 1$$

RLC CIRCUIT, FIGURE 16	$\theta = 45°$

It is noted that in a pure resistive circuit, theta equals zero. In a pure inductive or capacitive reactive circuit, theta equals 90°. In a circuit where R equals X, theta is midway or 45° as shown above.

CONCLUSIONS

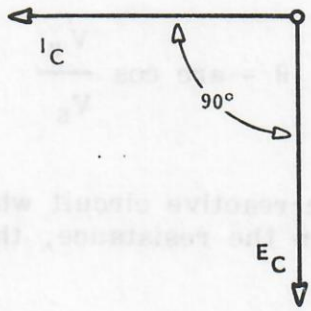
Voltage drops in a series resistive-reactive circuit, if added directly, will exceed the source voltage.

Voltage drops in a series resistive-reactive circuit can be added using phasors or the Pythagorean Theorem.

In a Right Triangle one of the three angles must measure 90°.

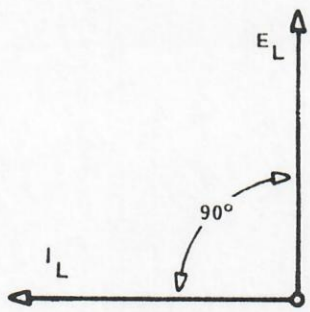
In a capacitive circuit the current leads the voltage by 90°.

The phasor representation of capacitive voltage and current is:



In an inductive circuit the current lags the voltage by 90°.

The phasor representation of an inductive voltage and current is:



The impedance of a resistive-reactive series circuit is determined by a phasor construction or calculated from:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The current flow in a resistive-reactive series circuit is determined from:

$$I = \frac{E}{Z}$$

The phase angle in a series resistive-reactive circuit is the angular difference between the applied voltage and the circuit current flow.

The phase angle, labeled theta (θ), can be determined from one of the following relationships:

$$\theta = \text{arc sin } \frac{V_C}{V_S} \qquad \theta = \text{arc cos } \frac{V_R}{V_S} \qquad \theta = \text{arc tan } \frac{V_C}{V_R}$$

In a series resistive-reactive circuit where the reactance is much greater than the resistance, theta will be close to 90 degrees.

In a series resistive-reactive circuit where the resistance is much greater than the reactance, theta will be close to zero degrees.

ASSIGNMENT

Answer the following multiple choice questions.

1. The voltage drops around a series RL circuit may be added using:

   a. instantaneous values.
   b. a phasor diagram.
   c. the Pythogorean Theorem.
   d. all of the above.

2. In a Right Triangle:

   a. two of the three angles must add up to 90°.
   b. all the angles must add up to 180°.
   c. if both sides are equal in length, two of the angles are 45°.
   d. all of the above.

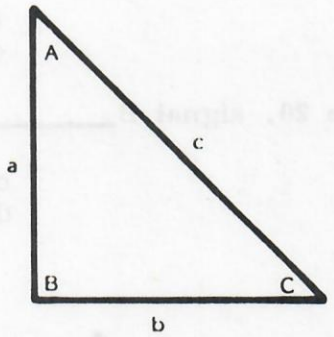


Figure 19 refers to questions 3 and 4.

3. In the triangle shown in Figure 19, the hypotenuse is side_____and the altitude is side_____.

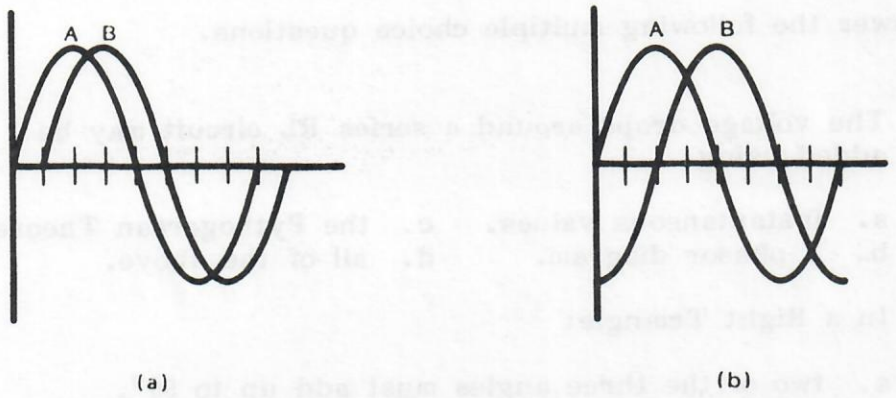
   a. a, c.
   b. c, a.
   c. c, b.
   d. b, a.

4. In the triangle shown in Figure 19, given that angle B is 90° and angle C is 42°, angle A must be:

   a. 90°.
   b. 48°.
   c. 45°.
   d. 42°.

5. Given the length of the altitude and base of the triangle in Figure 19, the length of the hypotenuse is:

   a. unable to be calculated.
   b. equal to a + b/2.
   c. $\sqrt{a + b/2}$.
   d. $\sqrt{a^2 + b^2}$.



(a) (b)

Figure 20 refers to questions 6 and 7.

6. In (a) of Figure 20, signal A_____signal B by _____.

a. leads; 45°.
b. lags; 45°.
c. lags; 90°.
d. leads; 90°.

7. In (b) of Figure 20, signal B_____signal A by _____.

a. leads; 45°.
b. lags; 45°.
c. leads; 90°.
d. lags; 90°.

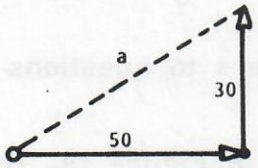


Figure 21 refers to questions 8 and 9.

8. The phasor diagram in Figure 21 represents a circuit that contains:

a. series R and L.
b. series R and C.
c. series resistance only.
d. series reactances only.

9. For the unit values shown in Figure 21, the length of (a) is equal to:

a. $30 + 50/2$.
b. $\sqrt{50/30}$.
c. $\sqrt{50^2 + 30^2}$.
d. $\sqrt{50^2 - 30^2}$.

10. In an series RL circuit:

    a. I_R lags the source voltage, V_S.
    b. V_S leads the circuit current, I_R.
    c. the phase difference between I_R and V_S is less than 90°.
    d. all of the above.

11. When drawing a phasor diagram for an RC circuit:

    a. V_C will have to be drawn pointed upward from V_R at the angle it lags V_S.
    b. V_R is the reference and V_C will be at 90° to V_R.
    c. V_S and V_R must be at 90° with V_S lagging.
    d. none of the above.

12. A 6000 ohm resistor is wired in series with a capacitor that when connected across an ac voltage has an X_C of 8000 ohms. The circuit impedance is closest to:

    a. 14,000 Ω
    b. $\sqrt{14,000\ \Omega}$
    c. 10,000 Ω
    d. none of the above.

13. A 6 K resistor and an 8 K reactance are wired in series across a 100 volt source. The current flow is closest to:

    a. 10 mA.
    b. 0.001 A.
    c. 0.016 A.
    d. 53.1 mA.

14. To determine the phase angle of an RC circuit given that R and X_C are known, the equation to use is:

    a. arc sin $\frac{R}{X_C}$
    b. arc tan $\frac{X_C}{R}$
    c. arc sin $\frac{Z}{X_C}$
    d. arc sin $\frac{X_C}{R}$

15. Given that in a series RC circuit, R = 10 K and X_C = 20 K, the phase angle is closest to:

    a. 63.4°
    b. 26.5°
    c. 34.9°
    d. 89°

16. A series RC circuit has a phase angle of 44°. When the frequency is increased:

    a. X_C increases.
    b. θ decreases.
    c. Z increases.
    d. none of the above.

17. In a series RLC circuit the reactance is equal to:

a. $X_L + X_C$
b. $(X_L)(X_C)$
c. $(X_L - X_C)$
d. $(X_L^2 - X_C^2)$

18. A series RLC circuit contains a 3 K resistance, a 10 K capacitive reactance and a 6 K inductive reactance. The circuit impedance is closest to:

a. 19 K
b. 9 K
c. 7 K
d. 5 K

19. The phase angle of an RLC circuit containing a 3 K resistance, a 10 K capacitive reactance and a 6 K inductive reactance is_____ degrees with I _____ the source voltage.

a. 53°; leading
b. 53°; lagging
c. 63.4°; leading
d. 63.4°; lagging

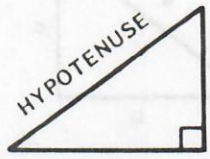
20. Given that, in a series RLC circuit, V_R is 30 volts, V_C is 40 volts and V_L is 90 volts, the source voltage is closest to:

a. 160 volts.
b. 80 volts.
c. 58 volts.
d. insufficient data to compute.

KEY TERMS

1. HYPOTENUSE

   The side of a right triangle opposite to the right angle.



2. IMPEDANCE (Z)

   The resulting total opposition to the flow of alternating current when both resistance and reactance (X_L or X_C) are in the circuit. Impedance is defined as Z and is measured in ohms.

3. LAG

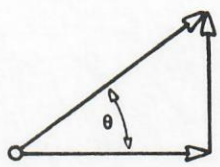
   The difference, in time, between two ac signals of the same frequency, measured in degrees between 0 and 360.

4. LEAD

   The opposite of LAG, above. A measurement of the difference in time between two ac signals of the same frequency, measured in degrees.

5. PHASE ANGLE (θ)

   The number of degrees by which the current leads or lags the applied voltage in an ac reactive circuit. The phase angle is indicated by the Greek letter theta, θ. It maybe shown on a phasor diagram as

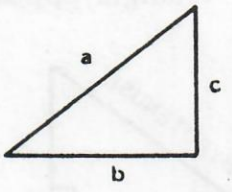


6. PHASOR DIAGRAM

   A phasor, also known as a vector, is used in electronics to indicate magnitude and direction as compared to a reference quantity.

7. PYTHAGOREAN THEOREM

The Pythagorean Theorem states that in a right triangle $a^2 = b^2 + c^2$ where



8. REACTANCE (X)

Opposition to the flow of ac by an inductor or capacitor. Reactance is measured in ohms and indicated as X (X_C or X_L).

9. RIGHT TRIANGLE

A triangle in which one of the three angles measures 90°.

Series RC Circuits 3

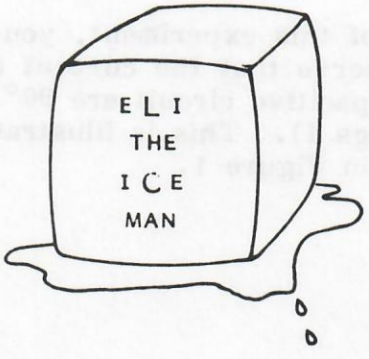
OBJECTIVES

When you finish this experiment, you will be able to:

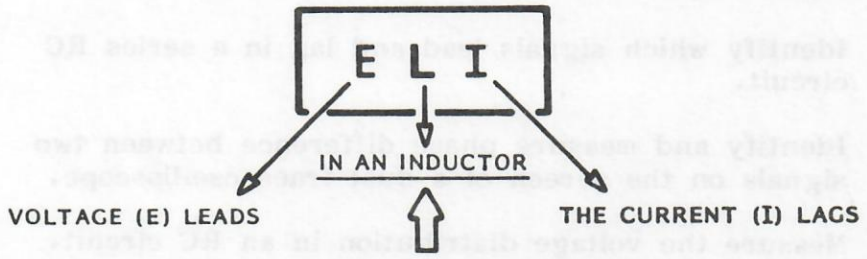
1. Identify which signals lead and lag in a series RC circuit.
2. Identify and measure phase difference between two signals on the screen of a dual trace oscilloscope.
3. Measure the voltage distribution in an RC circuit.
4. Add the RC circuit voltages graphically and by formula.
5. Calculate and measure the impedance of an RC circuit.
6. Display the 90° lead of the current versus voltage in a capacitor on an oscilloscope.
7. Calculate the phase angle in an RC circuit and display the phase shift on the oscilloscope.

DESCRIPTION

The ac voltage (E) and current (I) sine wave relationships were described in Information Sheet 1 of this unit. To remember these relationships more easily, the following aid may be used.

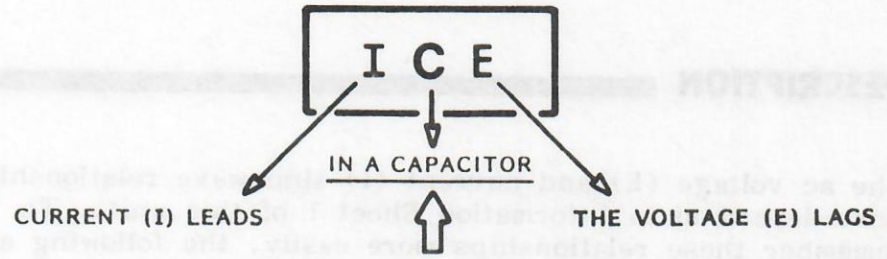


In an inductor (L), the voltage (E) appears before (or leads) the current (I). Thus:



To say that the voltage leads the current is simply another way of saying that in an inductor the current lags the voltage.

In a capacitive circuit (C), the current (I) appears before or leads the voltage. Thus:



Again, in a capacitor, to say that the current leads the voltage is another way of saying that the voltage lags the current.

In the first part of this experiment, you will use an oscilloscope to observe that the current and voltage waveforms in a capacitive circuit are 90° apart and that I leads E (or E lags I). This is illustrated by the two waveforms shown in Figure 1.

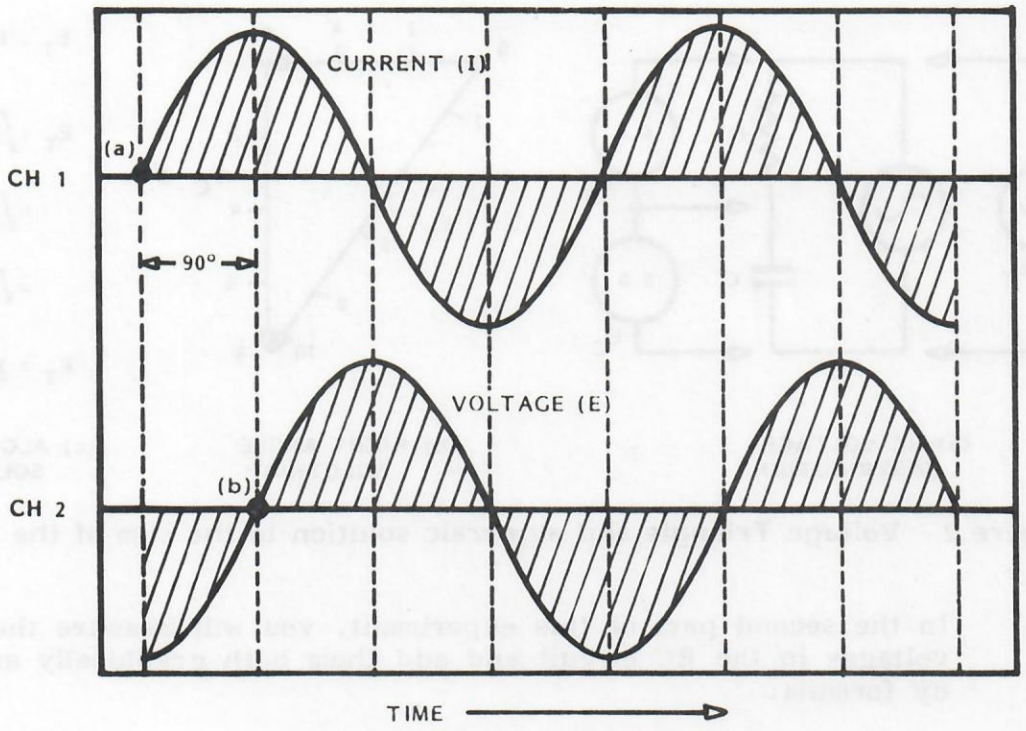
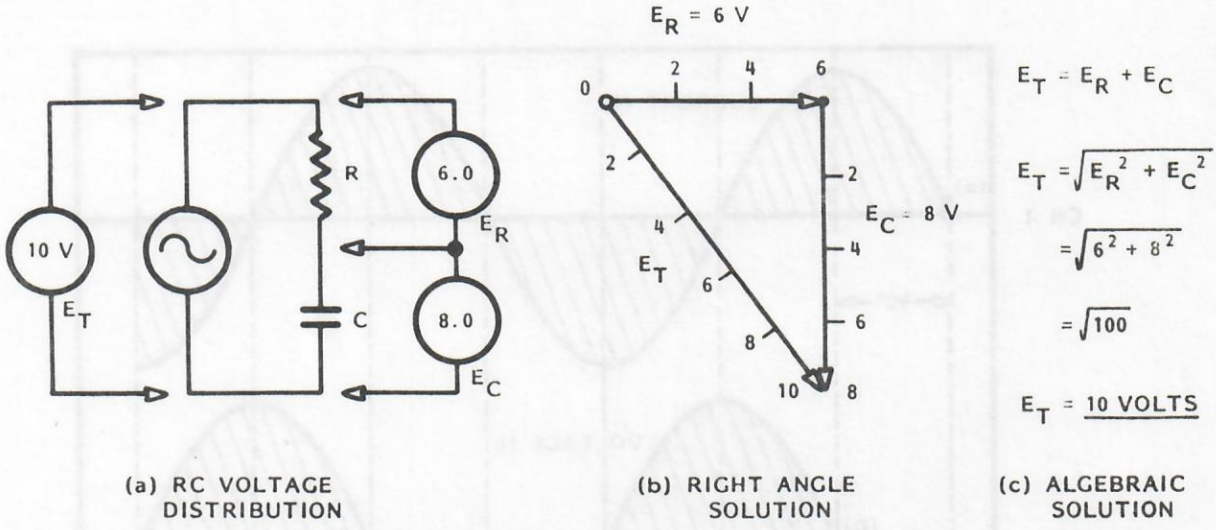


Figure 1 - Current and voltage 90° apart in a capacitive circuit.

The two waveforms shown in Figure 1 are 90° apart or have a "90° phase difference." Which waveform is leading the other? The CH 1 waveform is leading by 90° because its zero crossover (a) or the start of the cycle occurs before the zero crossover (b) of the CH 2 waveform.

RC VOLTAGE DISTRIBUTION

As explained in Information Sheet 1, the voltage drops in a series RC or RL circuit cannot be added directly because they are not in phase but 90° out of phase. Voltages that are 90° out of phase, such as in the RC circuit of Figure 2, when added directly, will exceed the source voltage which is contrary to the dc Kirchhoff's law as explained in an earlier experiment. The voltages must be added using the right triangle or the formula; "the square root of the sum of the squares" (the Pythagorean theorem).



(a) RC VOLTAGE DISTRIBUTION

(b) RIGHT ANGLE SOLUTION

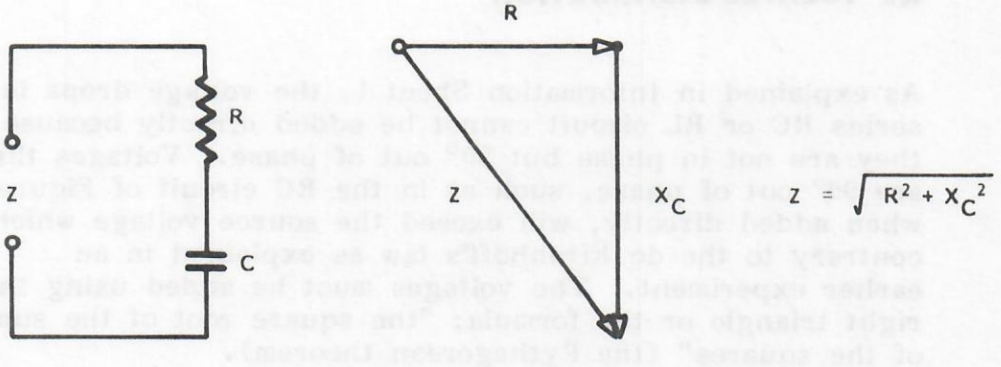
(c) ALGEBRAIC SOLUTION

Figure 2 - Voltage Triangle and algebraic solution to the sum of the voltages.

In the second part of this experiment, you will measure the voltages in the RC circuit and add them both graphically and by formula.

IMPEDANCE

In the third part of the experiment, you will verify the impedance triangle and formula calculations by measurement. Recall that R and X_C cannot be added directly. Either the Impedance Triangle must be constructed and the length of the hypotenuse measured as in Figure 3 or the "square root of the sum of the squares" may be used as shown in Figure 3.



(a) CIRCUIT

(b) RIGHT TRIANGLE METHOD

(c) FORMULA METHOD

Figure 3 - Methods of calculating impedance.

PROCEDURE

1. Wire the circuit shown in Figure 4.

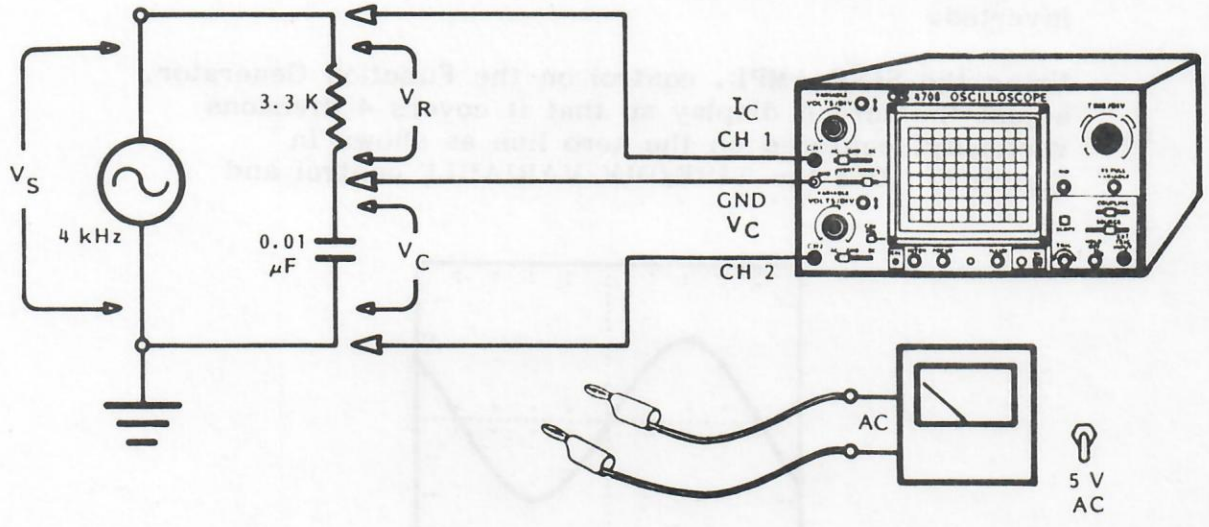


Figure 4 - RC Circuit EXPERIMENT.

3.1 CURRENT VERSUS VOLTAGE WAVEFORMS

2. Set the Function Generator to 4 kHz and the Function Generator voltage control to approximately mid-point.

3. Set the oscilloscope controls as follows:

CH 1 & CH 2 V/DIV	1 V/DIV
VERT MODE	CH 1
TIME/DIV	20 μS
SYNC SOURCE	CH 1
CH 2 INVERT SWITCH	DEPRESSED

4. The CH 1 trace represents the current in the capacitor. It is the voltage drop across the 3.3 K resistor and this voltage drop across R is in phase with the current flowing through R. The current flowing through R is the same as the current flowing through the capacitor. Thus, the CH 1 display represents I_C.

The CH 2 trace represents the voltage across the capacitor. The CH 2 input must be set to INVERT because the scope ground is not connected to the circuit ground so that the CH 2 voltage, V_C, is fed to the scope inverted.

Using the SINE AMPL. control on the Function Generator, adjust the screen display so that it covers 4 divisions vertically, centered on the zero line as shown in Figure 5. Use the TIME/DIV VARIABLE control and

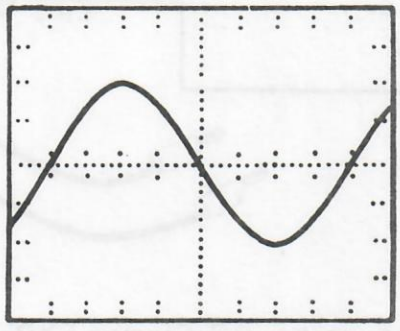


Figure 5 - Oscilloscope display for step 4.

the HORIZ CENT control to adjust the display time base so that the zero crossover is at the center and each half of the cycle covers 4 divisions as shown. Thus each division represents 45°.

5. Switch the VERT MODE from CH 1 to ALT (both CH 1 and CH 2.)

   Adjust the CH 2 display so that it covers approximately 4 divisions vertically using the CH 2 VARIABLE vertical control.

   Be sure that the CH 2 POL switch is set at invert to properly display the voltage across the capacitor. Looking at the circuit in Figure 4, note that the two scope leads connected across C are the reverse of the normal connections to properly observe voltage polarity. In order to correct for this, it was necessary to depress the CH 2 POL switch as directed before.

6. To clearly distinguish between the two signals that may be overlapped, rotate the CH 2 Vertical Position control back and forth. This moves the voltage trace, V_C, up and down so you can see which trace represents V_C. Observe that the V_C trace peak corresponds to the zero crossover of the current trace. This indicates a 90° delay of the voltage with respect to the current.

Draw the CH 2 voltage trace, shown on the screen, on Figure 5. Be sure to maintain the correct phase difference. Observe that the voltage waveform positive going crossover occurs 2 divisions after the current positive going crossover. The voltage is delayed by 90°.

Do the results confirm ICE from "Eli the Ice Man?" _____

7. Change the Function Generator frequency from 4 kHz to 2 kHz and readjust the TIME/DIV controls.

Does the phase shift of 90° change with frequency? _____

3.2 RC CIRCUIT VOLTAGES

8. Readjust the Function Generator frequency to 4 kHz.

Connect the ac panel meter (set for 5 VAC) across the Function Generator output, V_S.

Adjust the SINE AMPL. control for a sine voltage of 4 volts rms.

9. Using the ac meter, read the circuit voltage drops and enter them in Table 1.

V_S	4 V
V_R	V
V_C	V

TABLE 1 - RC circuit voltages.

10. Add the two voltage drops directly.

$$V_R + V_C =$$

$$(\quad) + (\quad) =$$

$V_R + V_C =$ _____ V

How does the sum compare to the source voltage, V_S? _____

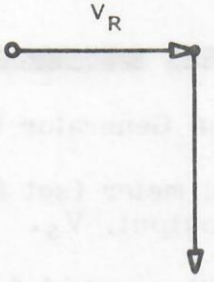
_____

_____

$V_C + V_R$ should be greater than the source voltage. You cannot add the two voltages directly, as explained in Information Sheet 1, when there is a 90° phase difference between the two voltages.

GRAPHICAL METHOD

11. Refer to the graph in Figure 6. Let each small division of the graph equal 0.2 volts. V_R is plotted horizontally and V_C is plotted vertically.



12. Add V_R and V_C by constructing a Right Triangle on the graph of Figure 6.

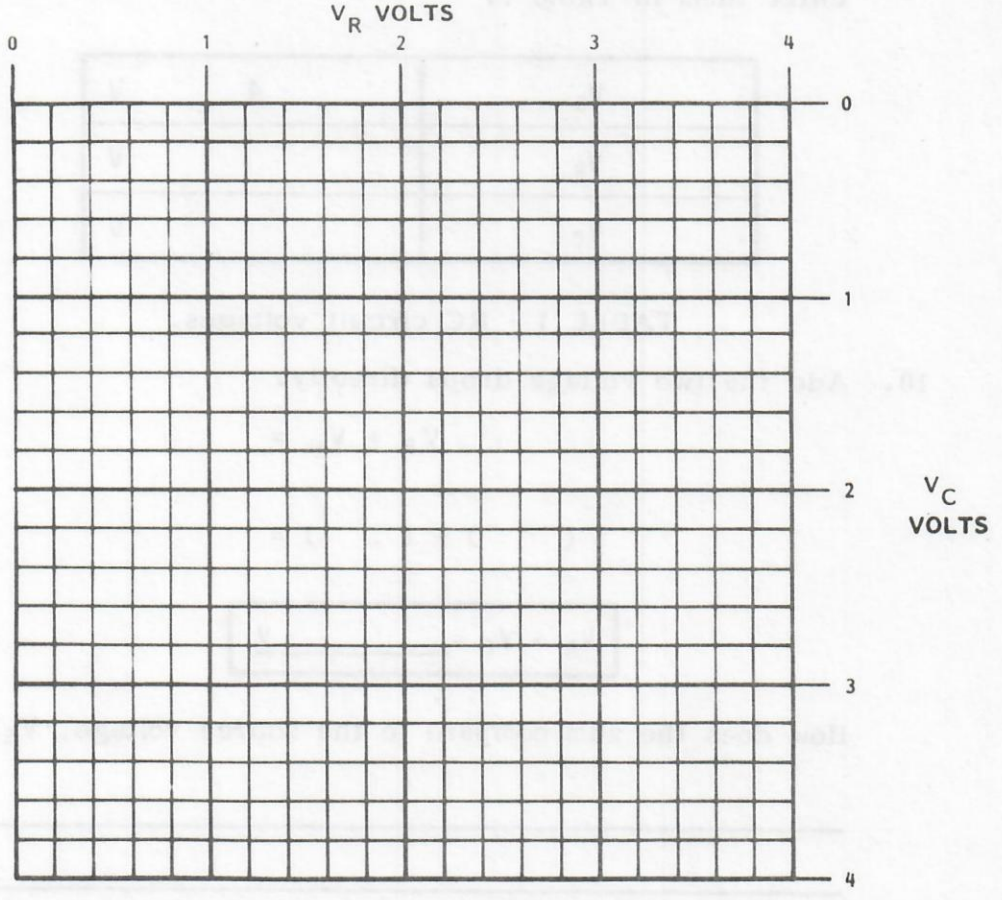


Figure 6 - Graph for construction of triangle solution.

Determine V_T graphically by measuring the length of the hypotenuse where 1 inch equals 1 volt.

HYPOTENUSE LENGTH	_____ INCHES = _____ VOLTS

How does the V_T answer obtained by construction compare to V_S measured in step 9?

_____

MATHEMATICAL CALCULATION

13. Calculate V_T from the individual voltage drops using the equation.

$$V_T = \sqrt{V_R^2 + V_C^2}$$

$$= \sqrt{(\quad)^2 + (\quad)^2}$$

$$= \sqrt{(\quad)}$$

V_T = _____ V

How does the calculated V_T above compare with V_S measured in step 9?

_____

_____

FREQUENCY VARIATION

14. Observe the waveform on the oscilloscope again.

Set the TIME/DIV switch to 0.2 mS.

Vary the Function Generator frequency slowly from 1 kHz to 10 kHz and back again.

Describe what happens to the amplitudes of the two signals (I_C and V_C) as the frequency changes and explain why.

_____

_____

_____

3.3 IMPEDANCE

15. R and X_C cannot be added directly. They must be added using the right triangle in a graphic manner or calculated by formula (Figure 7). The resulting total opposition to current flow when both R and X_C are in the circuit is called the IMPEDANCE, Z, and it is measured in ohms.

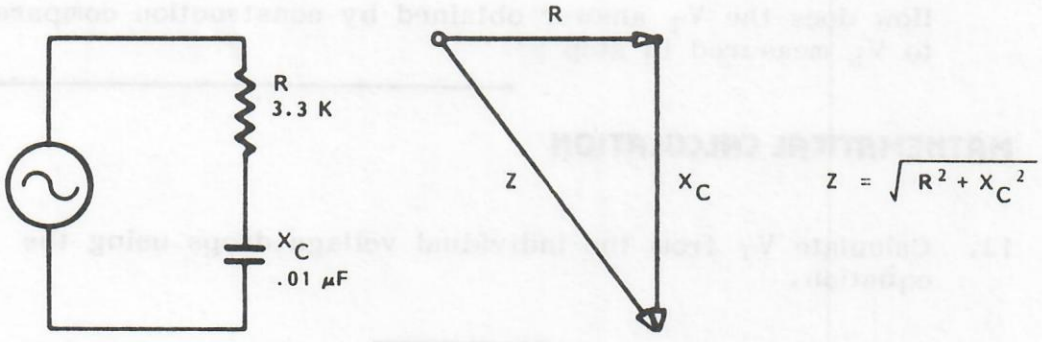


Figure 7 - Impedance triangle and equation.

Based on the measurements made earlier in step 9, it is possible to determine the impedance, Z, of our RC circuit.

The current flow in the circuit, I, is:

$$I = \frac{E}{R} = \frac{V_R}{3.3\ K}$$

Calculate I by substituting V_R from step 9:

$$I = \frac{(\quad)}{3.3\ K}$$

I = _____ mA

16. Calculate the total circuit impedance from our measurements using Ohm's Law for ac. Use I from Step 15 above and V_S measured earlier at 4v.

$$R = \frac{E}{I}$$

$$Z = \frac{V_S}{I} = \frac{4}{(\quad)}$$

Z BASED ON MEASUREMENTS	Z = _____ OHMS

17. The theoretical impedance is calculated below with the capacitive reactance calculated first.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{(6.28)(4 \times 10^3)(0.01 \times 10^{-6})}$$

$$= \frac{1{,}000{,}000}{251.2}$$

X_C = 3980 ohms = 3.98 K

We now calculate the total theoretical impedance from:

$$Z = \sqrt{R^2 + X_C{}^2}$$

Because R equals 3.3 K, we have:

$$Z = \sqrt{(3.3)^2 + (3.98)^2} = 5.17 \text{ K}$$

Z BASED ON THEORETICAL CALCULATION	Z = 5170 OHMS

Recall that the capacitor value can vary by ±20% and the resistor by ±5%. Also taking into account meter error, the measured impedance (step 16) and the calculated theoretical impedance above will match very closely.

3.4 RC PHASE ANGLE

18. The Phase Angle of an RC network is the same for both impedance and voltage, and is the number of degrees by which the current in the circuit leads the applied voltage. It is also the number of degrees by which the impedance lags zero degrees. This was explained in Information Sheet 1 and is illustrated again in Figure 8.

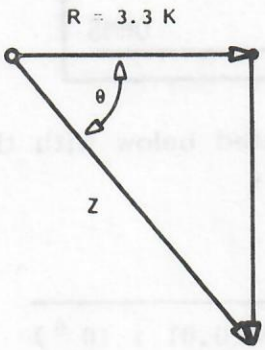


Figure 8 - Phase angle plot and trigonometric equation.

19. The circuit phase angle is calculated using the trigonometric function shown below with X_C as calculated in step 17.

$$\theta = \text{arc tan } \frac{X_C}{R}$$

$$= \text{arc tan } \frac{3980}{3300}$$

$$= \text{arc tan } 1.20606$$

THEORETICAL PHASE ANGLE	θ = 50.33°

NOTE: On some calculators, the ARC TAN key is labeled TAN $^{-1}$. On others, to obtain the ARC TAN function, you must press INV and then TAN.

20. Remove the three oscilloscope leads from the circuit.

Connect the oscilloscope into the circuit as shown in Figure 9 to measure the phase angle.

Channel 1 measures the input voltage, V_S.

Channel 2 measures the input current, I_S.

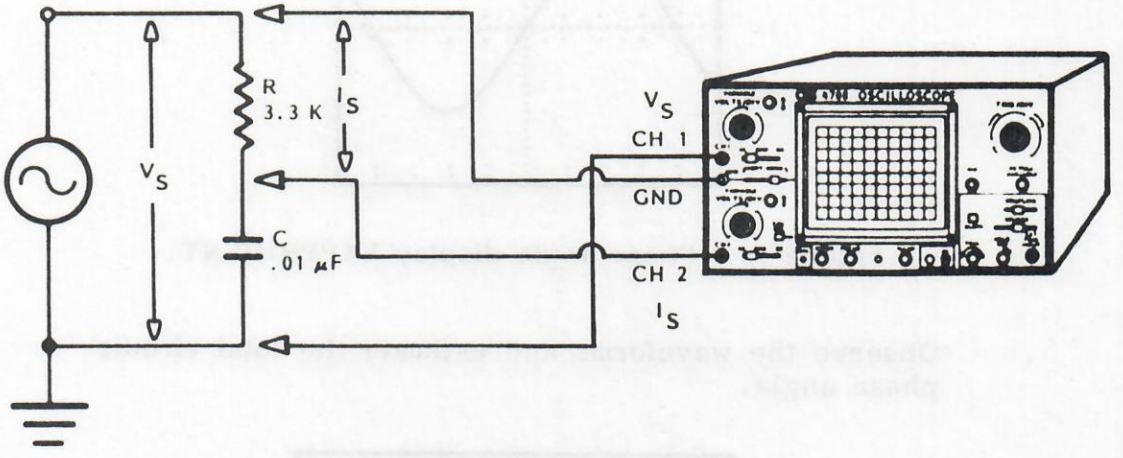


Figure 9 - Phase angle measurement EXPERIMENT.

21. Set the Function Generator to 4 kHz.

Set the oscilloscope controls as follows:

CH 1 V/DIV	1 V	VERT MODE	CH 1
CH 2 V/DIV	0.5 V	TIME/DIV	20 μS
CH 2 INVERT	NORMAL	SYNCH SOURCE	CH 1

22. Adjust the TIME/DIV VARIABLE control and the HOR CENT control so that each half of the sine wave covers 4 horizontal divisions on either side of the vertical center line as shown in Figure 10. Each division (cm) corresponds to 45°.

23. Switch the VERTICAL MODE from CH 1 to ALT to also display the CH 2 input, the circuit current.

Adjust the CH 2 Vertical Position control so that the current is also centered on the zero line.

Draw the CH 2 current waveform with the correct phase in the space provided in Figure 10 and label the signal.

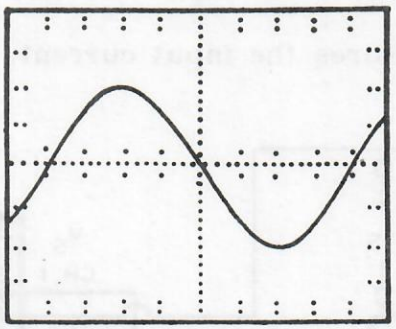


Figure 10 - Phase angle display EXPERIMENT.

Observe the waveforms and estimate the total circuit phase angle.

MEASURED θ = _____

The phase angle measured on the oscilloscope screen should be very close to that calculated earlier in step 19.

24. Increase the Function Generator frequency and observe the phase angle. As the frequency is increased, θ will approach 0° (E and I in phase) because as f goes up, X_C decreases and the circuit becomes more resistive.

    Decrease the frequency and observe the phase angle; θ will approach 90°. As the frequency is decreased, X_C increases and the circuit becomes more capacitive.

CONCLUSIONS

We have learned from this experiment that:

In a capacitive circuit, I leads E by 90°.

The mnemonic used to help memorize the lead and lag phases in reactive circuits is "ELI the ICE man."

Phase differences can be observed and measured on an oscilloscope.

The sum of the individual voltage drops will exceed the source voltage in an RC circuit because the voltages are out of phase.

The voltage drops in a series RC circuit may be added using the Right Triangle or added using the equation:

$$E_T = \sqrt{E_R^2 + E_C^2}$$

The total opposition to the flow of ac in an RC circuit is called IMPEDANCE and defined as Z.

Resistance and reactance in a series RL circuit cannot be added directly. They must be added using the Right Triangle (called the Impedance Triangle) or the equation:

$$Z = \sqrt{R^2 + X_C^2}$$

The phase angle of an RC network is the number of degrees by which the current leads the applied voltage. The phase angle is also the number of degrees by which the impedance leads the circuit resistance.

ASSIGNMENT

Answer the following multiple choice questions.

1. In a series RC circuit the:

   a. current leads the voltage by 90°.
   b. voltage lags the current by 90°.
   c. phase difference between E and I is 90°, maximum.
   d. all of the above.

2. In a series RC circuit, the leading or lagging component can be recalled from the mnemonic:

   a. ELI.
   b. ICE.
   b. MAN.
   d. all of the above.

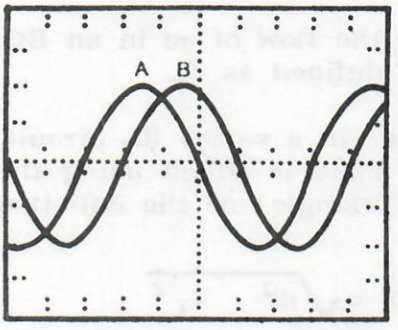


Figure 11 refers to question 3.

3. In Figure 11, signal:

   a. A leads signal B by 90°.
   b. B leads signal A by 90°.
   c. B lags signal A by 60°.
   d. A lags signal B by 60°.

4. A series RC circuit has a 10 volt drop across R and a 20 volt drop across C. The:

   a. source voltage is 22.4 volts.
   b. circuit impedance is 30 K.
   c. reactance equals half the resistance.
   d. all of the above.

5. The impedance in a series RC circuit is equal to:

   a. X_C plus R.
   b. R^2 plus X_C.
   c. R^2 plus X_C^2.
   d. none of the above.

6. The phase angle in a series RC circuit is the difference, in degrees, between the:

   a. circuit current and voltage source.
   b. voltage drop across the resistor and the voltage drop across the capacitor.
   c. current through the capacitor and the voltage drop across the capacitor.
   d. all of the above.

Solve the following problems showing all work.

7. A series RC circuit has a 12 volt drop across the resistance and an 18 volt drop across the capacitance. Find the source voltage algebracially.

8. A series RC circuit has a 4 volt drop across the series resistance and a 6 volt drop across the capacitor. Find the source voltage by constructing a right triangle. Proof the construction by calculating V_S by formula.

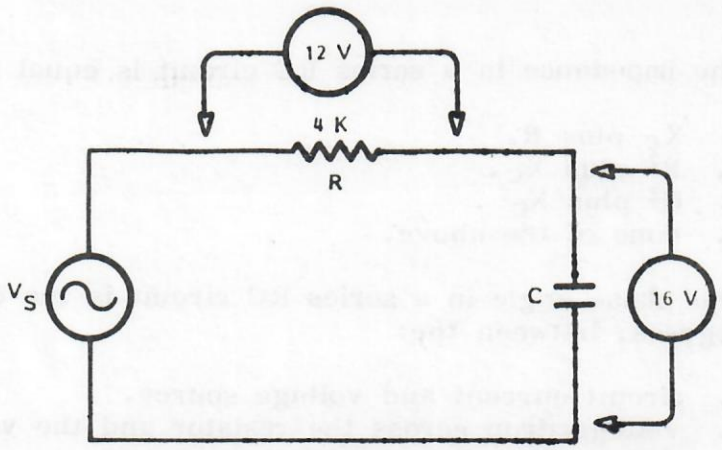


Figure 12 refers to questions 9 to 11.

9. Calculate the impedance of the RC circuit shown in Figure 12.

10. Calculate the value of the source voltage in the circuit of Figure 12.

11. Calculate the phase angle in the circuit of Figure 12.

12. Calculate the phase angle in a series RC circuit given that Z is 20 K and R is 4 K.

KEY TERMS

1. ELI

   A partial extract from the mnemonic "ELI the ICE man." It recalls that E is before I in an inductive circuit.

2. ICE

   A partial extract from the mnemonic "ELI the ICE man." It recalls that I is before E in a capacitive circuit.

3. IMPEDANCE

   The total opposition to current flow in a resistive and reactive circuit.

4. LAG

   To fall behind. In electronics it is a measurement, in degrees, of how far behind one signal is compared to another.

5. LEAD

   To precede or go before. In electronics, it is a measurement, in degrees, of how far ahead one signal is compared to another.

6. MNEMONIC

   An expression or device used to assist one's memory.

7. PHASE

   The angular difference, measured in degrees, between two electrical waveforms in an ac circuit.

8. PHASE ANGLE (θ)

   In an RC circuit it is the angular difference between the voltage source and the circuit current. It is indicated by the Greek letter theta, θ.

9. PHASE DIFFERENCE

   The time, measured in degrees, that one electrical waveform leads or lags another.

10. PHASE SHIFT

The difference, in degrees, between the input signal and the output signal.

11. REACTANCE

The opposition offered to the flow of ac by a capacitor (X_C) or an inductor (X_L).

12. RIGHT TRIANGLE

A triangle in which one of the three angles is 90°, a right angle.

13. THETA (θ)

The Greek letter, θ, is used to denote a phase angle.

Series RL Circuits 4

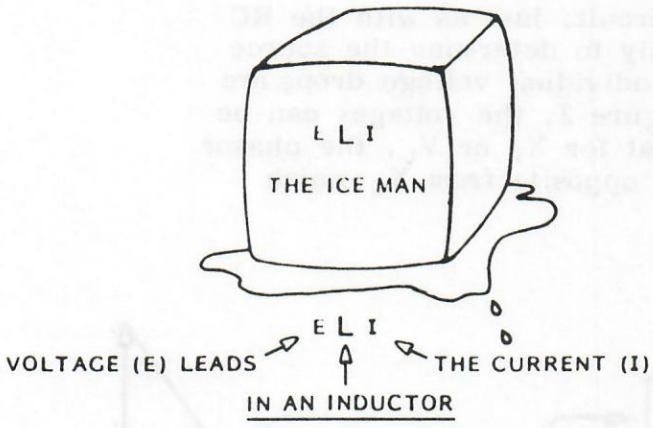
OBJECTIVES

When you finish this experiment, you will be able to:

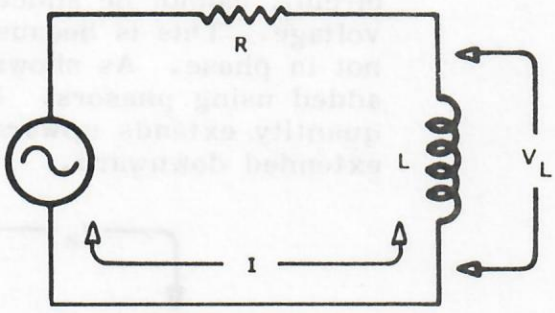
1. Identify which signals lead and lag in a series RL circuit.
2. Measure the voltage distribution in an RL circuit.
3. Add the RL circuit voltages using phasors and by formula.
4. Calculate and measure the impedance of an RL circuit.
5. Display the 90° current lag in the inductor on the oscilloscope.
6. Calculate the phase angle in an RL circuit and display the phase shift on the oscilloscope.

DESCRIPTION

The ac voltage and current relationships in an inductive circuit were described in Information Sheet 1 and, as noted, are 90° out of phase. This is similar to a capacitive circuit but now the current LAGS the voltage by 90°. To help remember this relationship, the aid used again is "ELI the ICE man" and it is shown in Figure 1(a).



(a) ELI THE ICE MAN



(b) SERIES RL CIRCUIT

Figure 1 - Series RL circuit and a memory aid for lagging current.

The current flow through the inductor, L, in Figure 1(b) and the voltage drop across the inductor are 90° out of phase with I lagging V. This would appear on our oscilloscope screen as shown in Figure 2.

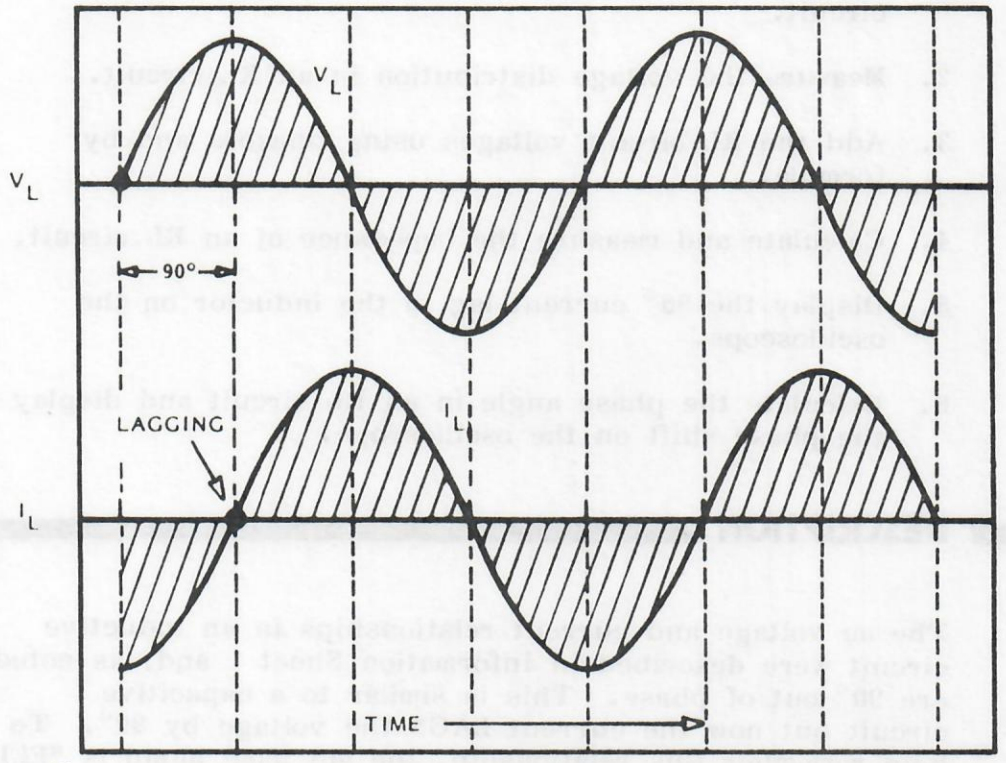


Figure 2 - Ninety degree phase shift created by an inductor.

RL VOLTAGE DISTRIBUTION

The voltage drops in the RL circuit, just as with the RC circuit, cannot be added directly to determine the source voltage. This is because the individual voltage drops are not in phase. As shown in Figure 3, the voltages can be added using phasors. Note that for X_L or V_L, the phasor quantity extends upward, 180° opposite from X_C which extended downward.

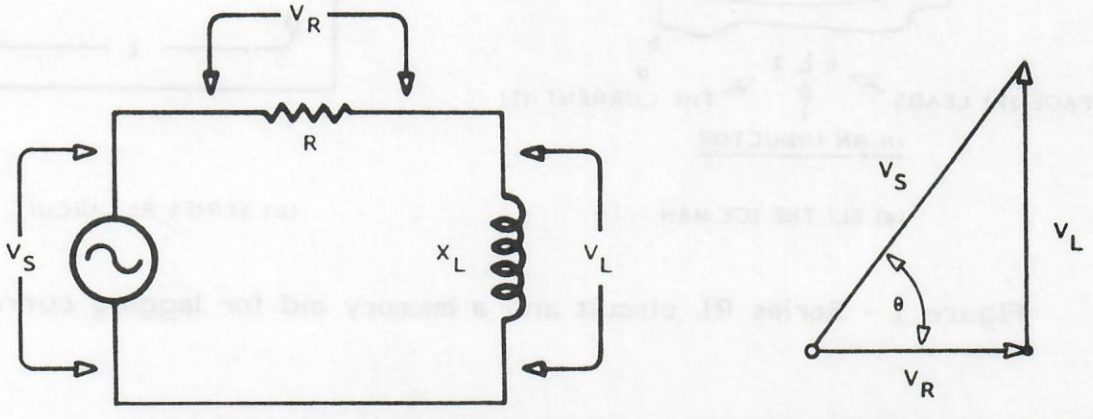


Figure 2 - Series RL circuit and its phasor diagram.

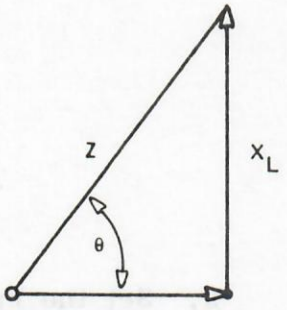
The source voltage can also be calculated using the equation below.

$$V_S = \sqrt{V_R^2 + V_L^2}$$

The impedance of the circuit can be determined by equation or phasor as shown below. The phase angle can also be determined.

$$Z = \sqrt{R^2 + X_L^2}$$

$$\theta = \arctan \frac{X_L}{R}$$



PROCEDURE

1. Wire the circuit shown in Figure 4.

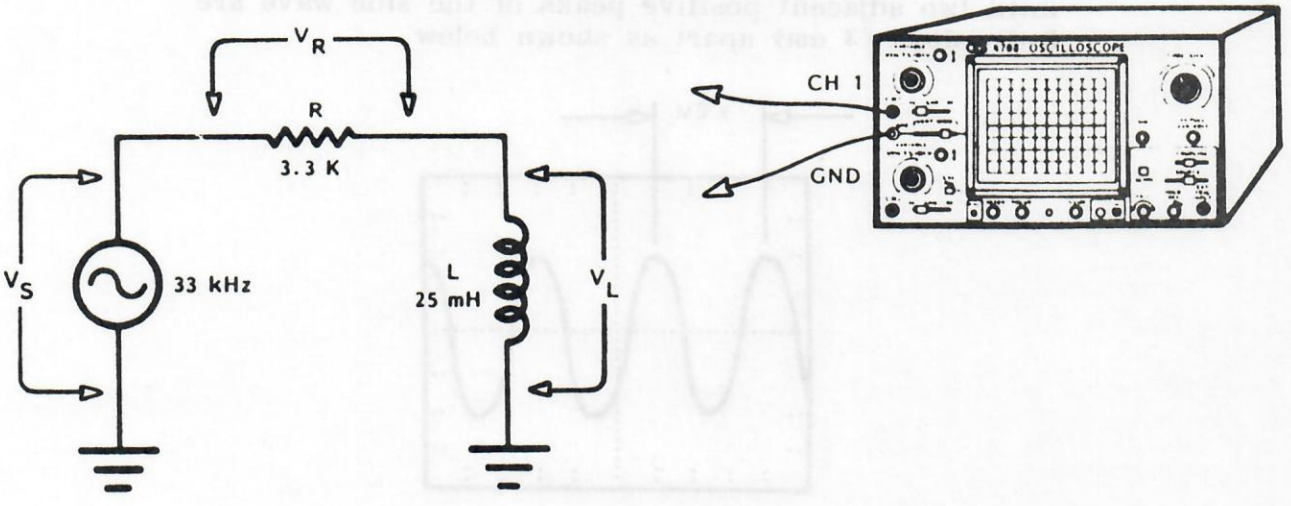


Figure 4 - RL circuit voltages; EXPERIMENT.

4.1 VOLTAGE DISTRIBUTION

2. In this experiment you will use the oscilloscope to measure the frequency and voltage simply to demonstrate another measurement technique.

   Connect the oscilloscope across V_S to adjust the frequency and voltage level.

   A frequency of 33 kHz has a period of:

$$T = \frac{1}{f}$$

$$= \frac{1}{33 \times 10^3}$$

$$T = 30\ \mu S$$

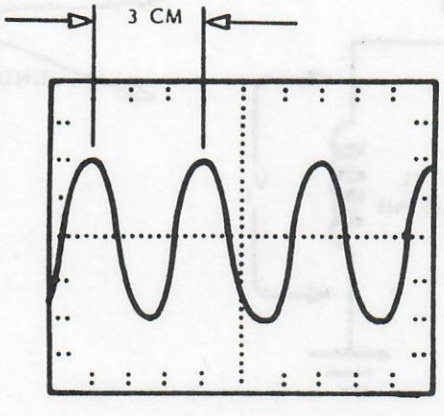
3. Set the Function Generator range switch to 10 K - 100 K and set the frequency at 20 kHz.

   Set the oscilloscope controls as follows:

CH 1 V/DIV	2	SYNC SOURCE	CH 1
VERT MODE	CH 1	TIME/DIV	10 μS

   Be certain that all oscilloscope VARIABLE controls are in the CALIBRATE position.

4. Adjust the FREQUENCY control of the Function Generator until two adjacent positive peaks of the sine wave are 3 divisions (3 cm) apart as shown below.



   This results in a frequency of 33 kHz.

5. Adjust the SINE AMPL. control of the Function Generator for 10 volts peak-to-peak or 5 divisions.

   Using the oscilloscope, read the voltages across the resistor and inductor and record them in Table 1.

V_S	10 V_{p-p}	⇦ PRESET
V_R	V_{p-p}	
V_L	V_{p-p}	

TABLE 1 - RL circuit voltages.

6. Check the voltage relationships by calculating the phasor sum of V_R and V_L.

$$V_T = \sqrt{V_R^2 + V_L^2}$$

$$= \sqrt{(\quad)^2 + (\quad)^2}$$

$$= \sqrt{(\quad) + (\quad)}$$

$$V_T = \qquad V$$

How does the above calculation of V_T compare with the measured V_S?

_____

_____

4.2 IMPEDANCE MEASUREMENT

7. The impedance of the RL circuit is easily determined from the measured source voltage and the circuit current.

$$\text{MEASURED } Z = \frac{V_S}{I_S}$$

where $$I_S = \frac{V_R}{R}$$

Determine the measured current from:

$$I_S = \frac{V_R}{R} = \frac{(\quad)}{3.3\ K}$$

I_S = _____ A

The impedance is then:

$$Z = \frac{V_S}{I_S} = \frac{(10)}{(\quad)}$$

MEASURED	Z = _____ OHMS

8. Calculate the theoretical impedance for the RL circuit by first finding X_L at 33 kHz.

$$X_L = 2\pi fL$$

$$= (6.28)(33 \times 10^3)(25 \times 10^{-3})$$

X_L _____ OHMS

Now, determine the theoretical impedance from:

$$Z = \sqrt{R^2 + X_L^2}$$

$$= \sqrt{(3.3)^2 + (\quad)^2}$$

THEORETICAL CALCULATION	Z = _____ OHMS

How close are the measured and theoretical impedance values? To what do you attribute the difference, if any?

_____

_____

_____

4.3 VOLTAGE-CURRENT PHASE IN AN INDUCTOR

9. Connect the oscilloscope into the circuit as shown in Figure 5. CH 1 measures the current, I_L in the inductor and CH 2 measures the inductor voltage.

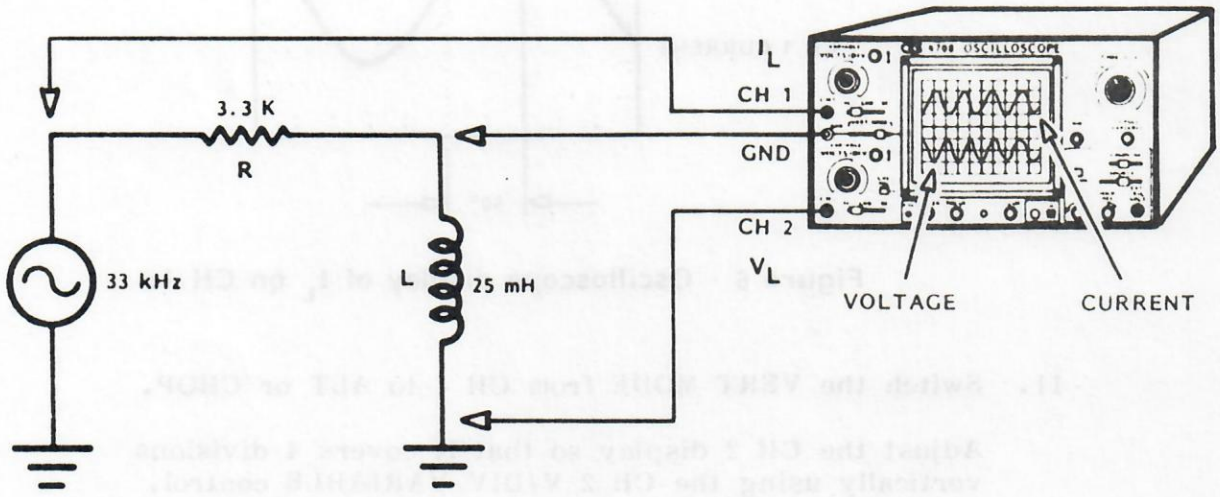


Figure 5 - Current and voltage phasors; EXPERIMENT.

10. Set the oscilloscope controls as follows:

CH 1 V/DIV	0.5 V	TIME/DIV	5 μS
CH 2 V/DIV	1 V	SYNC SOURCE	CH 1
VERT MODE	CH 1		

Adjust the CH 1 AMPLITUDE control so that the ac signal covers 4 divisions (4 cm) vertically. Adjust the Vertical Position so that the ac waveform is centered around the middle horizontal line on the oscilloscope screen.

Switch the TIME/DIV control to 2 μS and adjust the TIME/DIV VARIABLE and HOR POSITION controls so that one half cycle covers 4 divisions and is positioned exactly as shown in Figure 6. Each horizontal division is then 45°.

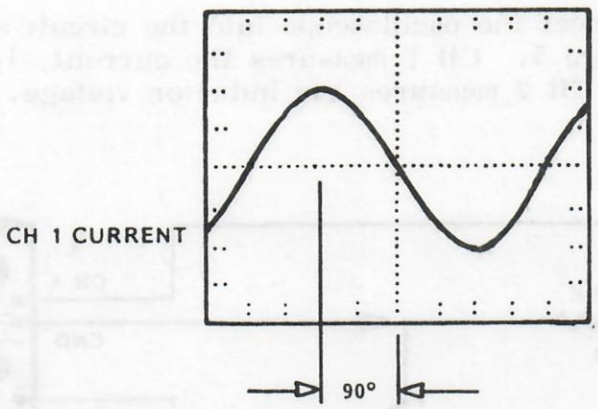


Figure 6 - Oscilloscope display of I_L on CH 1.

11. Switch the VERT MODE from CH 1 to ALT or CHOP.

    Adjust the CH 2 display so that it covers 4 divisions vertically using the CH 2 V/DIV VARIABLE control.

    Depress the CH 2 POL switch to INVERT to properly display the voltage waveform across the inductor.

12. Position the CH 2 waveform vertically so that it is alongside the CH 1 signal. Observe that the CH 2 voltage peak occurs before the CH 1 current peak.

    Does the CH 1 Current Signal lead or lag the CH 2 Voltage Signal? _____

    By how many degrees do the signals differ? Remember that each division equals 45°. _____

    Draw the CH 2 signal over the CH 1 signal in Figure 6.

4.4 RL PHASE ANGLE (θ)

13. The phase angle of an RL network is the number of degrees by which the current in the circuit lags the applied voltage and is also the angle of the impedance, Z. This was explained earlier in Information Sheet 1 and is illustrated in Figure 7.

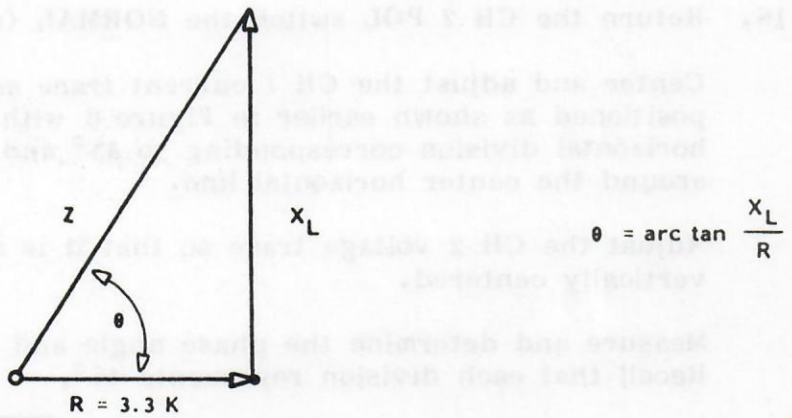


Figure 7 - Phase angle plot and trignometric solution.

14. Calculate the phase angle using the trigonometric function shown below. Use the inductive reactance calculated earlier in step 8.

$$\theta = \text{arc tan } \frac{X_L}{R}$$

$$\theta = \text{arc tan } \frac{(\quad)}{3.3}$$

θ = _____ degrees

15. To measure θ, remove the 3 wires to the oscilloscope and reconnect the oscilloscope as shown in Figure 8.

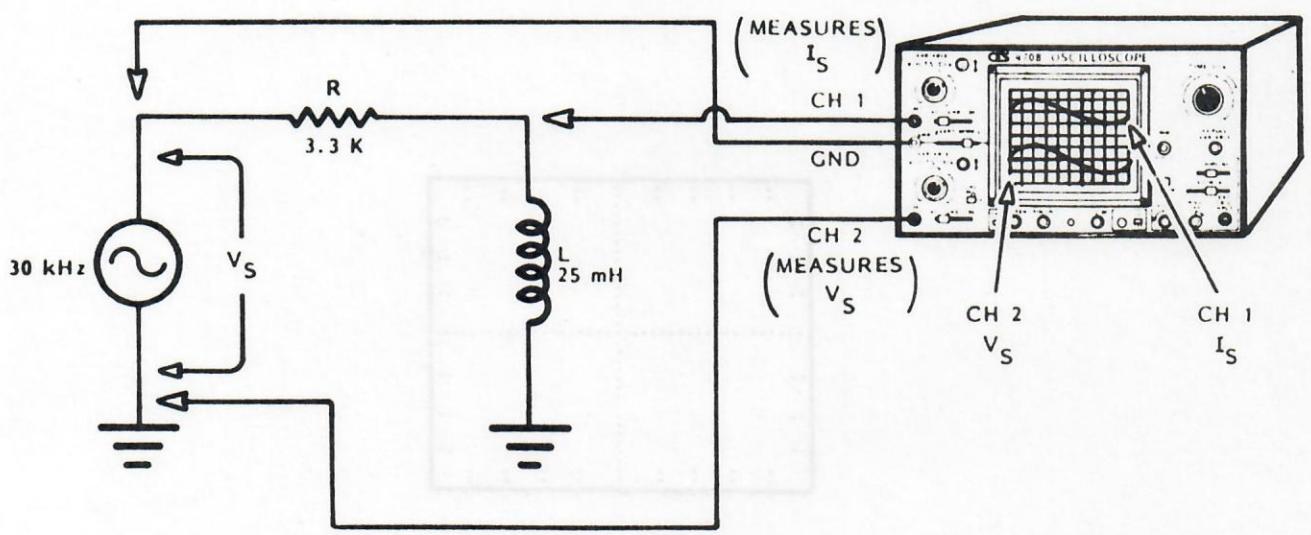


Figure 8 - Oscilloscope connections to view θ; EXPERIMENT.

16. Return the CH 2 POL switch the NORMAL (out).

Center and adjust the CH 1 current trace so that it is positioned as shown earlier in Figure 6 with one horizontal division corresponding to 45° and centered around the center horizontal line.

Adjust the CH 2 voltage trace so that it is also vertically centered.

Measure and determine the phase angle and lead or lag. Recall that each division represents 45°.

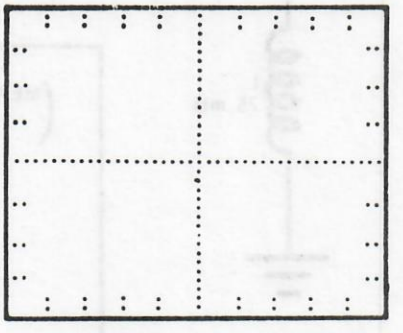
4.5 LOW FREQUENCY PHASE SHIFT

17. As the input frequency to the RL circuit is reduced, X_L drops. As X_L drops the phase angle is reduced. When X_L is near zero, the circuit is almost purely resistive and θ will be close to zero also.

Set the Function Generator frequency to 1 kHz. Set the TIME/DIV on the oscilloscope to 0.1 mS and adjust the TIME/DIV VARIABLE for 4 divisions over 180° of the sine wave.

Adjust the CH 2 signal to overlap the CH 1 signal.

18. Sketch and label the two waveforms below, showing their phase relationship.



Does the current lead or lag the voltage and by how much?

_____

_____

_____

The CH 1 and CH 2 signals should practically be in phase because the circuit is mostly resistive.

19. Calculate the inductive reactance at 1 kHz. We will then compare it to the 3.3 K resistance and to the X_L at 33 kHz (5181 ohms).

$$X_L = 2\pi fL$$

$$= (6.28)(1 \times 10^{3})(25 \times 10^{-3})$$

$$= (6.28)(1)(25)$$

At 1 kHz	X_L = _____ OHMS

At 1 kHz $\quad \theta = \arctan \dfrac{X_L}{R}$

$$= \arctan \frac{(\quad)}{3{,}300}$$

AT 1 kHz	θ = _____ DEGREES

How do X_L and θ, at 1 kHz, compare to these quantities at 33 kHz (X_L = 5181 ohms, θ = 57.5°)?

_____

_____

_____

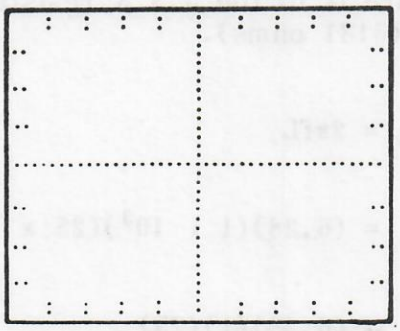
4.6 HIGH FREQUENCY PHASE SHIFT

20. Set the Function Generator to 100 kHz.

Set the TIME/DIV to 1 μS and adjust the CH 1 current signal for 8 horizontal divisions as done earlier (45° per division.)

Position the CH 2 voltage signal, over the CH 1 signal. Be sure both signals are vertically centered.

Sketch and label the two waveforms below, showing their phase relationship.



Does the current or the voltage lag and by how many degrees?

_____

_____

21. Calculate the theoretical inductive reactance at 100 kHz and compare it to X_L at 1 kHz and at 30 kHz and to the 3.3 K resistance.

$$X_L = 2\pi fL$$

$$= (6.28)(100 \times 10^3)(25 \times 10^{-3})$$

$$= (6.28)(100)(25)$$

(At 100 kHz)	X_L = _____ OHMS

How does X_L at 100 kHz compare to X_L at 1 kHz and at 30 kHz and to the 3.3 K resistance?

_____

_____

_____

22. Calculate the phase angle at 100 kHz using the following equation:

$$\theta = \text{arc tan} \frac{X_L}{R}$$

$$= \text{arc tan} \frac{(\quad)K}{3.3\ K}$$

(AT 100 kHz)	θ = DEGREES

How close is the calculated θ above to the measured θ from step 20?

CONCLUSIONS

We have learned from this experiment that:

The current in an inductor lags the voltage by 90°.

The mnemonic used to help memorize lead and lag in reactive circuits is "ELI the ICE man."

The sum of the individual voltage drops in a series RC circuit will exceed the value of the source voltage because the voltages are out of phase.

The voltage drops in a series RL circuit may be added using phasors or the "square of the sum of the squares" equation.

Resistance and reactance in a series RL circuit cannot be added directly. They must be added using phasors or the "square root of the sum of the squares" equation.

When constructing a phasor for an inductive circuit, the inductive quantity will point in the opposite direction of the capacitive quantity.

ASSIGNMENT

Answer the following True-False questions.

1. In a series RL circuit the voltage leads the current. ____

2. In a series RL circuit all the voltage drops add up to equal the source voltage in accordance with Kirchhoff's Law. ____

3. Given a voltage drop of 21 volts across R in a series RL circuit and 28 volts across L, the source voltage must be 35 volts. ____

4. An ac signal that has a frequency of 20 kHz has a period of 50 μS. ____

5. The sine wave on an oscilloscope screen is spread over 9 divisions. Three divisions equal 120 degrees. ____

6. In a series RL circuit the impedance of the inductor can be determined by measurement with an ohmmeter. ____

7. If both the inductor current and voltage drop are known in a series RL circuit, the inductor impedance still cannot be determined because the two quantities are not in phase. ____

8. In a series RL circuit the phase angle is the measurement, in degrees, of how much the current lags the source voltage. ____

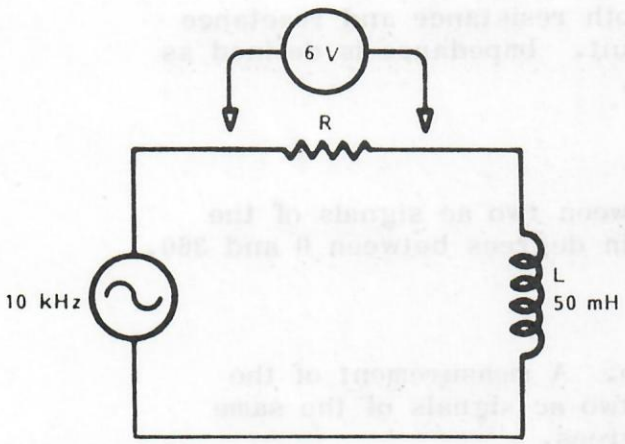
9. The phase angle in a series RL circuit can be calculated from: ____

$$\theta = \text{TAN}^{-1} \frac{X_L}{R}$$

10. As the input frequency to a series RL circuit is lowered, theta increases. ____

CALCULATIONS

11. Solve for the following showing all work.



a. I_{source}

b. X_L

c. V_L

d. V_S

e. Z

KEY TERMS

1. IMPEDANCE (Z)

   The resulting total opposition to the flow of alternating current when both resistance and reactance (X_L or X_C) are in the circuit. Impedance is defined as Z and is measured in ohms.

2. LAG

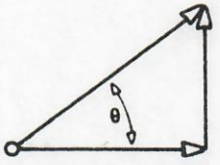
   The difference in time, between two ac signals of the same frequency, measured in degrees between 0 and 360.

3. LEAD

   The opposite of LAG, above. A measurement of the difference in time between two ac signals of the same frequency, measured in degrees.

4. PHASE ANGLE (θ)

   The number of degrees by which the current leads the applied voltage. The phase angle is defined by the Greek letter θ. It is shown on a phasor diagram as



5. PERIOD (T)

   The time required to complete one cycle in an ac waveform. The period, T, is measured in seconds and is given by

$$T = \frac{1}{f}$$

Series RLC Circuits 5

OBJECTIVES

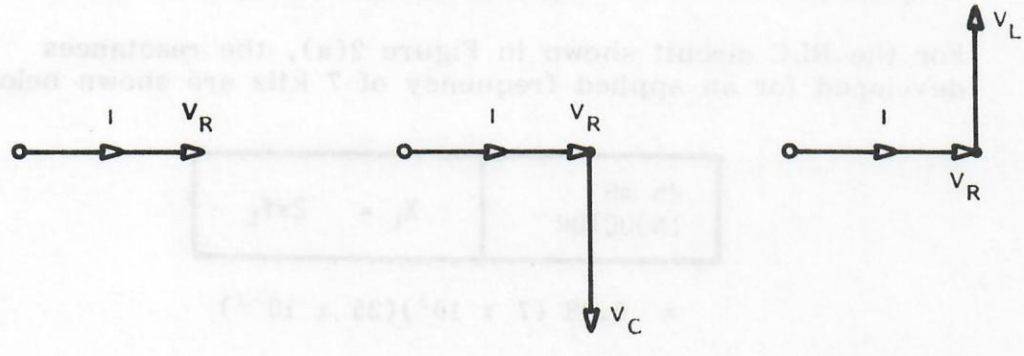
When you finish this experiment, you will be able to:

1. Plot the phasor diagram for a series RLC circuit.
2. Determine the individual component voltage drops in a series RLC circuit.
3. Calculate the current flow in a series RLC circuit.
4. Show that the voltage drops across L and C in a series RLC circuit are 180° out of phase, and cancel each other.
5. Calculate the impedance of a series RLC circuit.

DESCRIPTION

In a pure inductive circuit, the voltage leads the current by 90°. In a pure capacitive circuit, the voltage lags the current by 90°. In a resistive circuit the voltage and current are in phase. When all three components, L, C and R, are combined in a series circuit, the individual voltage drops cannot be added directly but must be added using phasor diagrams or by the square root of the sum of the squares.

The phasor for a resistive circuit is shown in Figure 1(a). Note that the current and the resultant voltage drop are in phase.

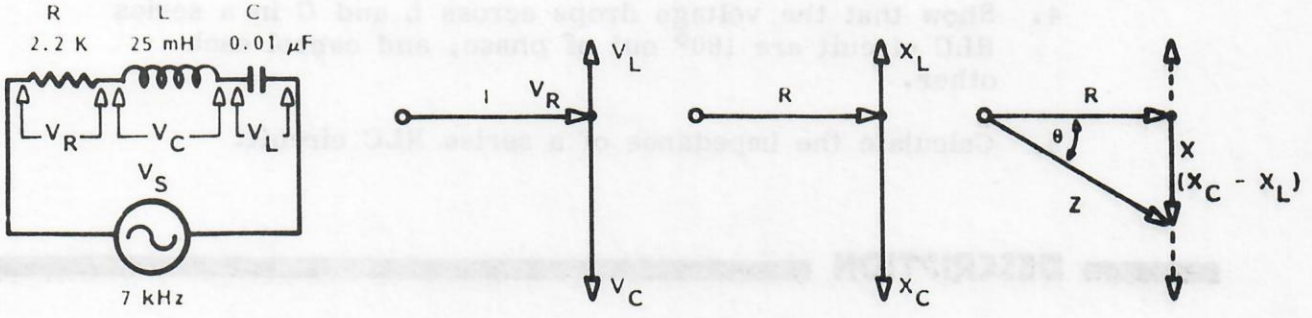


(a) RESISTIVE PHASOR (b) CAPACITIVE PHASOR (c) INDUCTIVE PHASOR

Figure 1 - Phasor representations for R, L and C.

Because the current is the same in each component of the series R, L, C circuit, the current (I) can be used as the reference and because V_R is in phase with I, V_R is the reference. Figure 1(b) shows the capacitive phasor. The voltage, V_C, lags V_R by 90°. The inductive phasor shown in Figure 1(c) shows that V_L leads the current by 90°.

Figure 2(a) shows a simple series circuit. The voltage phasors are shown in Figure 2(b). The impedance phasors are shown in Figure 2(c).



(a) SERIES RLC CIRCUIT (b) PHASOR CONSTRUCTION (c) IMPEDANCE PHASOR (d) PHASOR SOLUTION

Figure 2 - Series RLC circuit and its phasor solution.

Because X_C and X_L are opposite quantities, they cancel each other and the direction of the remainder corresponds to whichever of the two is greater in quantity. In this case, X_C is greater ($X_C - X_L$.) The resultant reactance and impedance phasor diagram is shown in Figure 2(d) where the remaining reactance is drawn and the phasor solution constructed. The circuit is effectively "capacitive" and has all the characteristics of the RC circuit, at this frequency, that were described earlier in Experiment 3.

For the RLC circuit shown in Figure 2(a), the reactances developed for an applied frequency of 7 kHz are shown below:

25 mH INDUCTOR	$X_L = 2\pi f_L$

$= 6.28\ (7 \times 10^3)(25 \times 10^{-3})$

$= 6.28 \times 7 \times 25$

THEORETICAL INDUCTIVE REACTANCE	$X_L = 1099$ OHMS

0.01 μF CAPACITOR	$X_C = \dfrac{1}{2\pi fC}$

$$= \frac{1}{6.28\ (7 \times 10^3)(0.01 \times 10^{-6})}$$

$$= \frac{10^3}{0.4396}$$

THEORETICAL CAPACITIVE REACTANCE	X_C = 2275 OHMS

The resultant impedance, Z, may be plotted using phasors or calculated using the following equation:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

$$= \sqrt{2.2^2 + (2.275 - 1.099)^2}$$

$$= \sqrt{4.84 + 1.38}$$

THEORETICAL IMPEDANCE	Z = 2.495 K

In this experiment, you will wire a series RLC circuit, measure the voltage distribution and observe how V_L and V_C cancel each other. You will calculate the theoretical V_S algebraically and compare it to the measured V_S. You will also calculate the actual circuit impedance and compare it to the theoretical value calculated above.

PROCEDURE

1. Wire the circuit shown in Figure 3.

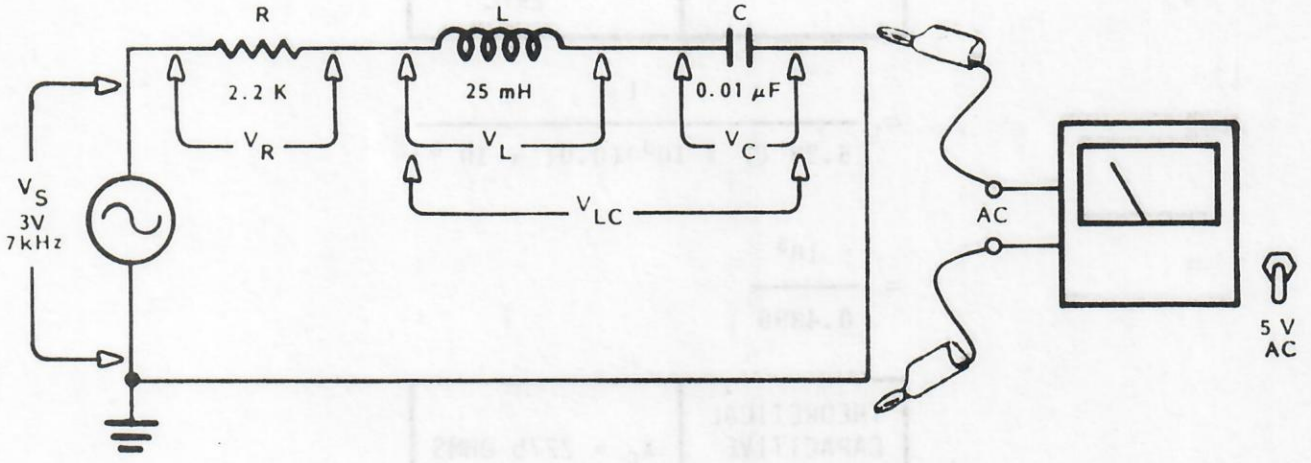


Figure 3 - Series RLC circuit EXPERIMENT.

5.1 SERIES RLC VOLTAGE DISTRIBUTION

2. Set the Function Generator frequency to 7 kHz.

3. Read V_S and adjust the Sine Ampl. control for a 3 volt rms signal source.

4. Read all the voltage drops and enter them in Table 1.

V_S	3 V	⇦ PRESET
V_R	V	
V_L	V	
V_C	V	
V_{LC}	V	

TABLE 1 - RLC circuit voltages.

5. Add all the individual voltage drops directly as shown below.

$$V_A = V_R + V_L + V_C$$

$$= (\quad) + (\quad) + (\quad)$$

$V_A =$ _____ V

How does V_A compare to V_S? Can the voltage drops be added directly? Why?

_____

_____

_____

_____

6. It was stated earlier, in the description, that V_L and V_C are each 90° out of phase with the circuit current. The result is that they are 180° out of phase with each other and thus cancel.

Calculate $V_C - V_L$ as shown below using the voltages listed in Table 1.

$$V_X = V_C - V_L = (\quad) - (\quad)$$

$V_X = V_C - V_L =$ _____ V

It is the above value of reactive voltage, V_X, that is used for further calculations. How does V_X compare to the voltage measurement V_{LC} in Table 1?

_____

_____

_____

7. Add the circuit voltages using the "square root of the sum of the squares" as shown below.

$$V_T = \sqrt{V_R^2 + (V_C - V_L)^2}$$

$$= \sqrt{(\quad)^2 + [(\quad) - (\quad)]^2}$$

$$= \sqrt{(\quad) + (\quad)}$$

V_T = _____ V

The voltage, V_T, should match very closely to V_S set at 3 volts.

5.2 IMPEDANCE CALCULATIONS

8. The total RLC series circuit impedance, Z, based on the measurements, may now be calculated. First calculate the current:

$$I_S = \frac{V_R}{2.2\ K}$$

$$= \frac{(\quad)}{2.2} \text{ mA}$$

I_S = _____ mA

Calculate the impedance:

$$Z = \frac{V_S}{I_S}$$

$$= \frac{3}{(\quad)} \text{ mA}$$

Z BASED ON MEASUREMENTS	Z = _____ K

How does the measured impedance compare to the theoretical impedance of 2495 ohms calculated in the description?

CONCLUSIONS

In an inductive circuit, I lags E by 90°.

In a capacitive circuit, I leads E by 90°.

When L and C are combined in a circuit, the leading and lagging voltages cancel each other.

When X_C and X_L are combined, the total reactance equals the difference between the two; $X_C - X_L$ or $X_L - X_C$.

The voltage drops across L and C, when measured in series, produce the difference as shown below.

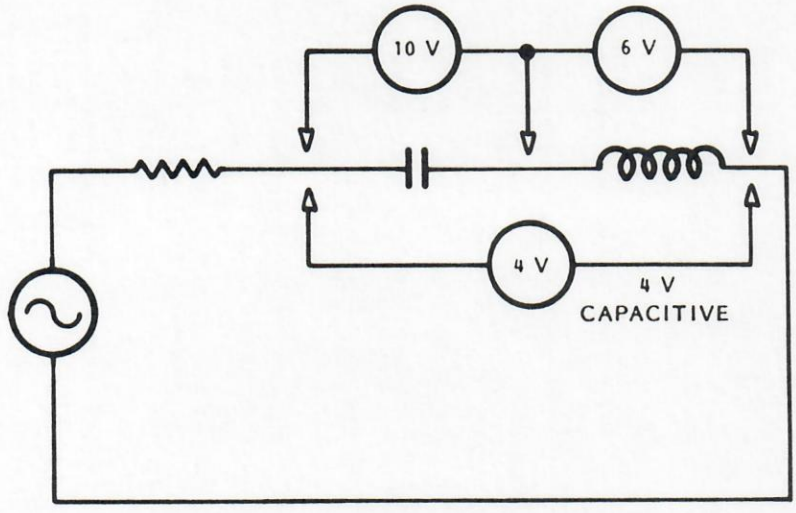
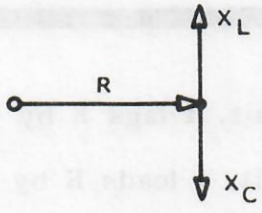


Figure 4

The impedance of an RLC circuit may be determined algebraically as follows:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

or by a phasor diagram and graphic construction.



The individual voltage drops may be added from:

$$V_S = \sqrt{V_R^2 + (V_C - V_L)^2}$$

ASSIGNMENT

Answer the following True-False questions.

1. The reactance of an inductor varies directly with frequency. _____

2. The reactance of a capacitor varies inversely with frequency. _____

3. When an inductor and capacitor are placed in series, the reactances are additive. _____

4. The reactance of a 0.05 μF capacitor at 10 kHz is approximately 320 ohms. _____

5. The reactance of a 500 mH inductor at 10 kHz is approximately 31,400 ohms. _____

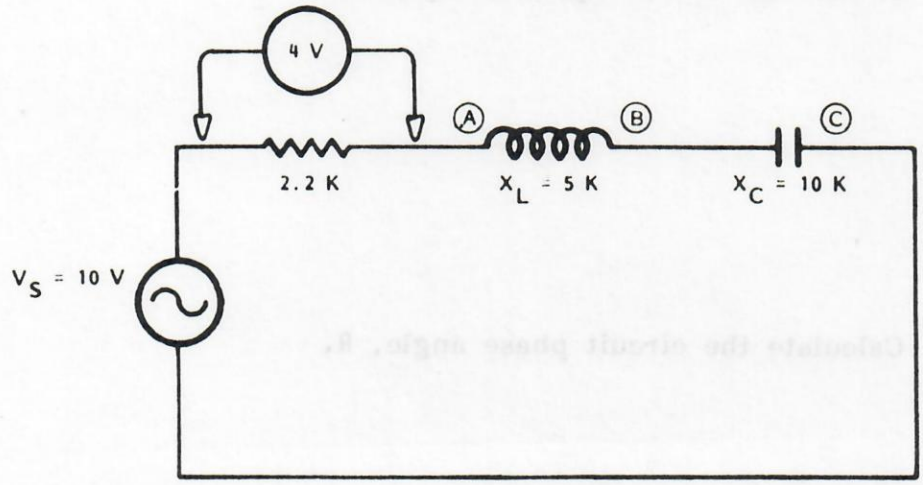


Figure 5 refers to questions 6 to 10.

6. The impedance of the RLC circuit, shown in Figure 5, is approximately 5.5 K. _____

7. Given the value of X_L shown in Figure 5, the voltage drop across L is close to 18 volts. _____

8. Given the value of X_C shown in Figure 5, the voltage drop across C is 9 volts. _____

9. The voltage measured from A to C in Figure 5 is approximately 9 volts with the reactive voltage lagging V_R. ____

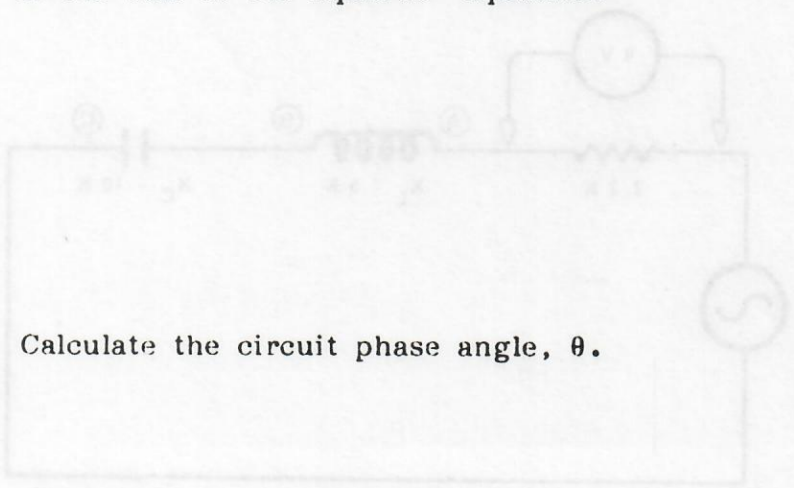
10. For the circuit shown in Figure 5, under average conditions, X_L always equals X_C. ____

Perform the following:

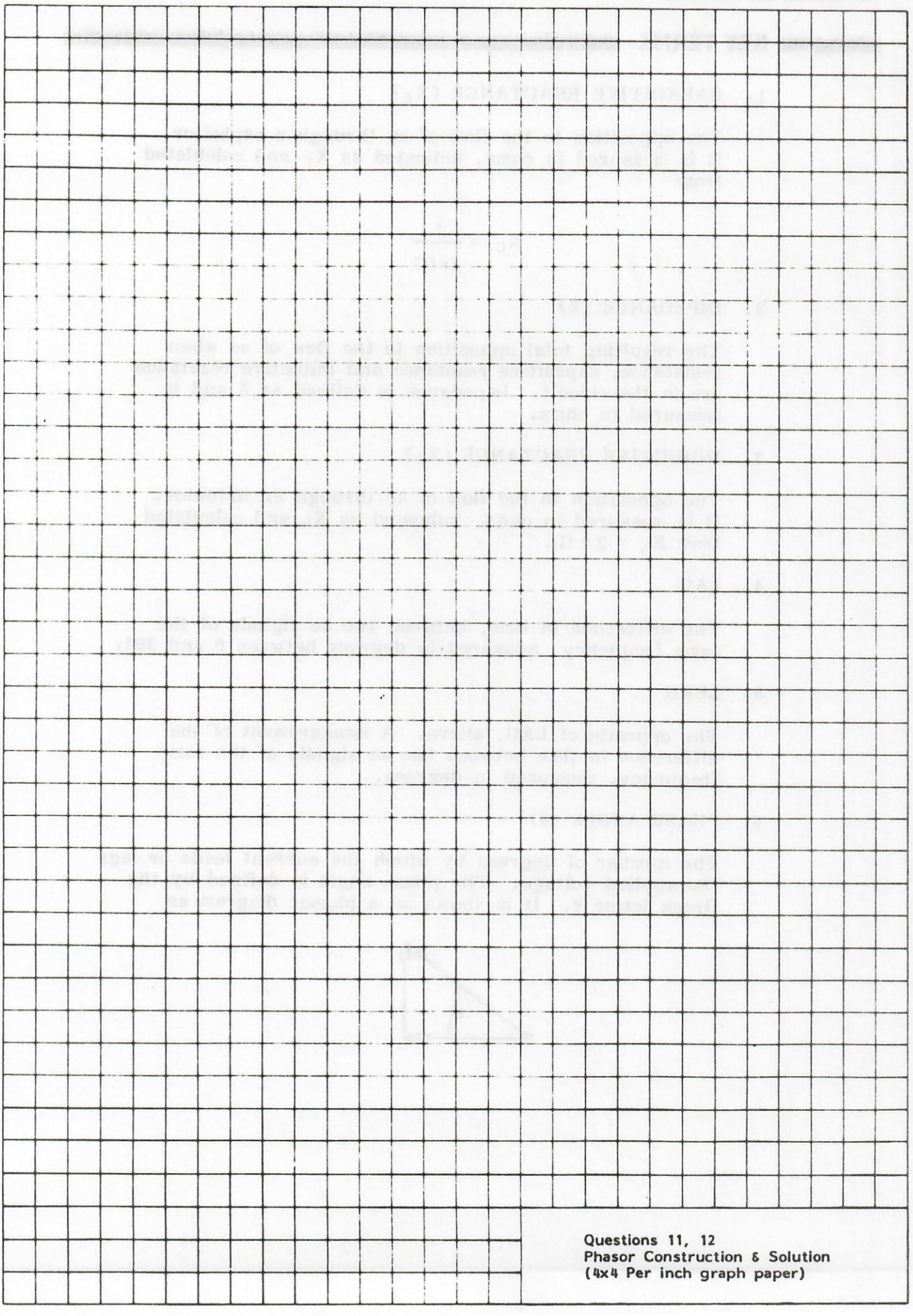
11. Construct a phasor, to scale, for an RLC circuit consisting of a 3 K resistor, a 6 K capacitive reactance and a 4 K inductive reactance on the graph paper provided.

12. Solve for the circuit impedance using the phasor construction.

13. Solve for the circuit impedance using the "square root of the sum of the squares" equation.



14. Calculate the circuit phase angle, θ.



Questions 11, 12
Phasor Construction & Solution
(4x4 Per inch graph paper)

KEY TERMS

1. CAPACITIVE REACTANCE (X_C)

   The opposition to the flow of ac through a capacitor. It is measured in ohms, indicated as X_C and calculated from

$$X_C = \frac{1}{2\pi fC}$$

2. IMPEDANCE (Z)

   The resulting total opposition to the flow of ac when resistance, capacitive reactance and inductive reactance are in the circuit. Impedance is defined as Z and is measured in ohms.

3. INDUCTIVE REACTANCE (X_L)

   The opposition to the flow of ac through an inductor. It is measured in ohms, indicated as X_L and calculated from $X_L = 2\pi fL$.

4. LAG

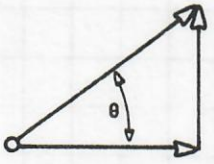
   The difference in time, between two ac signals of the same frequency, measured in degrees between 0 and 360.

5. LEAD

   The opposite of LAG, above. A measurement of the difference in time between two ac signals of the same frequency, measured in degrees.

6. PHASE ANGLE (θ)

   The number of degrees by which the current leads or lags the applied voltage. The phase angle is defined by the Greek letter θ. It is shown on a phasor diagram as



7. PHASOR

A phasor, also known as a vector, is used to indicate magnitude and direction as compared to a reference quantity. This is illustrated in 6 above.

8. REACTANCE (X)

Opposition to the flow of ac by an inductor or capacitor. Reactance is measured in ohms and indicated as X (X_C or X_L).

Parallel RLC Circuits 6

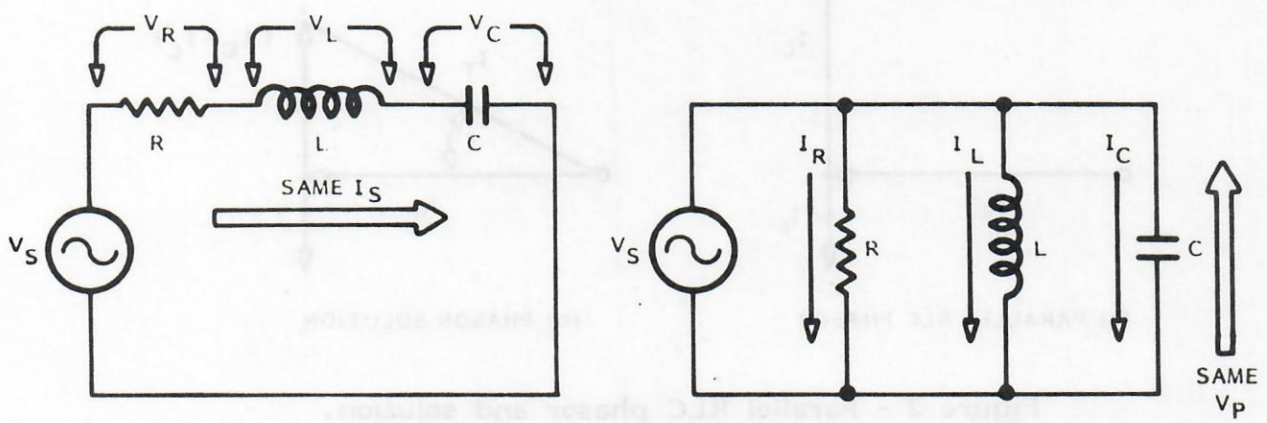
OBJECTIVES

When you finish this experiment, you will be able to:

1. Draw the phasor diagram of a parallel RL, RC and RLC circuit and solve them.
2. Measure the current distribution in the parallel RLC circuits.
3. Calculate the total circuit impedance, Z_T, using the branch impedance values.
4. Calculate the total circuit impedance, Z_T, using the branch current values.

DESCRIPTION

In the previous experiments involving R, L and C, these components have been wired in series combinations. This experiment explores the effects of placing the R, L and C components in parallel.



(a) SERIES RLC (b) PARALLEL RLC

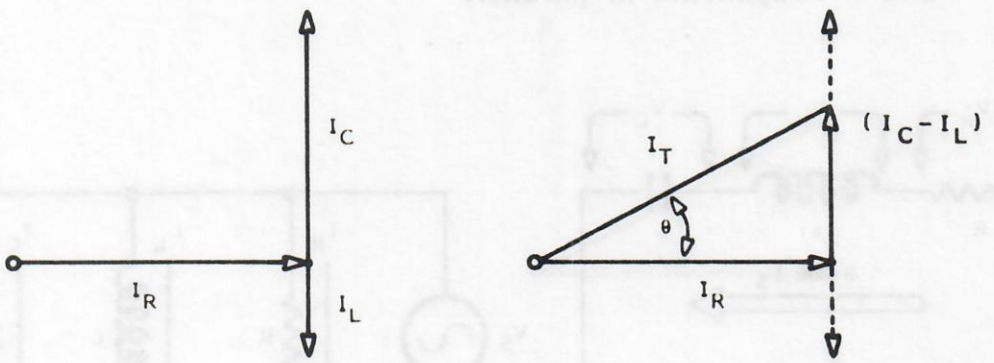
Figure 1 - Series and parallel RLC circuits.

In the series circuit shown in Figure 1(a), the current is the same through all the components, that is, the current phase in each component is the same. The individual voltage drops are all out of phase. The voltage across R is in phase with I; the voltage across L leads I by 90° while voltage across C lags I by 90°.

In the parallel RLC circuit shown in Figure 1(b), the voltage across each component is the same as in any parallel circuit. The branch currents, however, are all different. In the resistive branch, V and I are in phase. In the inductive branch, I lags by 90° and in the capacitive branch, I leads by 90°.

PARALLEL RLC PHASOR

Because the voltage across each branch of the RLC network is the same, the phasor diagram for this type of circuit must be presented using the branch currents, I_R, I_L, and I_C. A phasor for R, L and C is shown in Figure 2(a).



(a) PARALLEL RLC PHASOR (b) PHASOR SOLUTION

Figure 2 - Parallel RLC phasor and solution.

In Figure 2(a) and (b), I_R is used as the reference quantity because it is in phase with the applied voltage. The capacitor current, I_C, leads by 90° as shown in the phasor construction. The inductor current, I_L, lags by 90°. To solve the phasor, the $I_C - I_L$ resultant is drawn and the hypotenuse added. The construction can be measured to determine the length of the hypotenuse (total current, I_T) and the phase angle, θ, (theta).

PARALLEL RLC IMPEDANCE EQUATIONS

The impedance of a series RLC circuit can be solved by constructing a phasor diagram or by using the equation previously studied and repeated below.

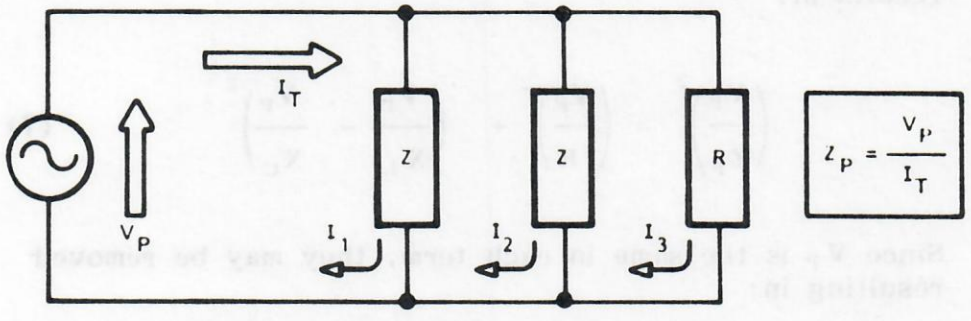
SERIES IMPEDANCE EQUATION	$Z = \sqrt{R^2 + (X_L - X_C)^2}$

(1)

Remember, even if $(X_L - X_C)$ is negative, it becomes, positive when squared.

Calculating the impedance of a parallel RLC combination is more difficult. The basic equation for the parallel circuit is derived below.

The total parallel impedance, Z_P, is defined simply as the voltage divided by the current.



(2)

where Z_P = parallel impedance
V_P = voltage across the parallel network
I_T = total current drawn by the parallel network

The total current, I_T, is the sum of the inductive, capacitive and resistive currents and since they are all out of phase with each other, they cannot be added directly but are added as phasors as shown on the next page.

$$I_T^2 = I_R^2 + (I_L - I_C)^2 \quad (3)$$

where

$$I_R = \frac{V_P}{R} \quad (4)$$

$$I_L = \frac{V_P}{X_L} \quad (5)$$

$$I_C = \frac{V_P}{X_C} \quad (6)$$

Substituting equations (2), (4), (5) and (6) into (3) results in:

$$\left(\frac{V_P}{Z_P}\right)^2 = \left(\frac{V_P}{R}\right)^2 + \left(\frac{V_P}{X_L} - \frac{V_P}{X_C}\right)^2 \quad (7)$$

Since V_P is the same in each term, they may be removed resulting in:

$$\left(\frac{1}{Z_P}\right)^2 = \left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2 \quad (8)$$

Taking the square root of both sides produces:

PARALLEL Z_P EQUATION	$\frac{1}{Z_P} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}$	(9)

This can also be rearranged as follows:

$$Z_P = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}} \quad (10)$$

If only one of the reactive components, X_L or X_C (denoted as X), is in parallel with the resistance, then equation (10) can be simplified as shown below.

$$Z_P = \frac{1}{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X}\right)^2} \tag{11}$$

Equation (11) can be rearranged as shown below.

FOR X_L OR X_C IN PARALLEL WITH R BUT NOT BOTH	$Z_P = \sqrt{\frac{R^2 \cdot X^2}{R^2 + X^2}}$

(12)

Note the similarity between the equation for parallel R and X and for two parallel resistors where:

FOR TWO PARALLEL RESISTORS	$R_P = \frac{R_1 \cdot R_2}{R_1 + R_2}$

(13)

If there is no resistance in the parallel network, only X_L and X_C, then the equation can be simplified as shown below.

$$Z_P = \sqrt{\frac{1}{\left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}} \tag{14}$$

$$Z_P = \frac{1}{\left(\frac{1}{X_L} - \frac{1}{X_C}\right)} \tag{15}$$

FOR NO PARALLEL RESISTOR	$Z_P = \frac{X_L \cdot X_C}{X_L - X_C}$

(16)

Again, note the similarity between equation (16) above and the parallel resistance equation (13).

ALTERNATE EQUATIONS FOR PARALLEL IMPEDANCE

A second method that may be used to solve for Z_P in RLC networks has a three step procedure but each step is fairly simple.

Step 1. It first requires that the individual branch currents be calculated as follows:

$$I_R = \frac{V_P}{R} \quad (17) \qquad I_L = \frac{V_P}{X_L} \quad (18) \qquad I_L = \frac{V_P}{X_C} \quad (19)$$

You can assume any voltage for V_P (typically V_P = 10 volts).

Step 2. When the three branch currents are known, they are added using the "square root of the sum of the squares" equation below:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2} \quad (20)$$

Step 3. Once I_T is known, the impedance is determined using the same V_P (10 volts) as before and I_T.

$$Z_P = \frac{V_P}{I_T} \quad (21)$$

PARALLEL RLC CALCULATIONS

A parallel RLC network operated at a frequency of 20 kHz is shown in Figure 3.

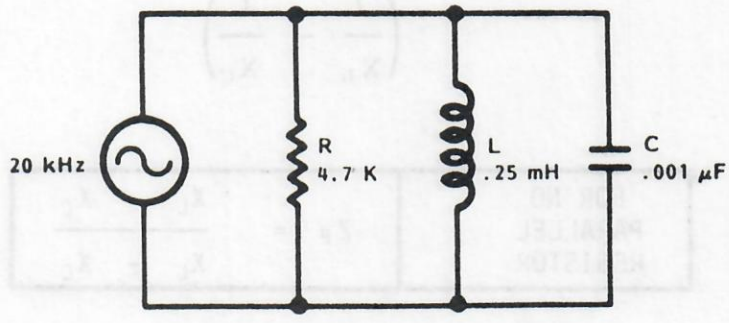


Figure 3 - Parallel RLC network example.

For a 20 kHz input, the opposition to the current flow in each branch is as follows:

R $\boxed{R = 4.7\ K}$

L $X_L = 2\pi fL = (6.28)(20 \times 10^3)(25 \times 10^{-3})$

$= (6.28)(20)(25)$

$\boxed{X_L = 3.14\ K}$

C $X_C = \dfrac{1}{2\pi fC} = \dfrac{1}{(6.28)(20 \times 10^3)(0.001 \times 10^{-6})}$

$= \dfrac{10^6}{(6.28)(20)}$

$\boxed{X_C = 7.96\ K}$

With the branch resistance and reactance values known, it is now possible to calculate the total impedance, Z_P, of three circuit combinations of R, L and C shown in Figure 4.

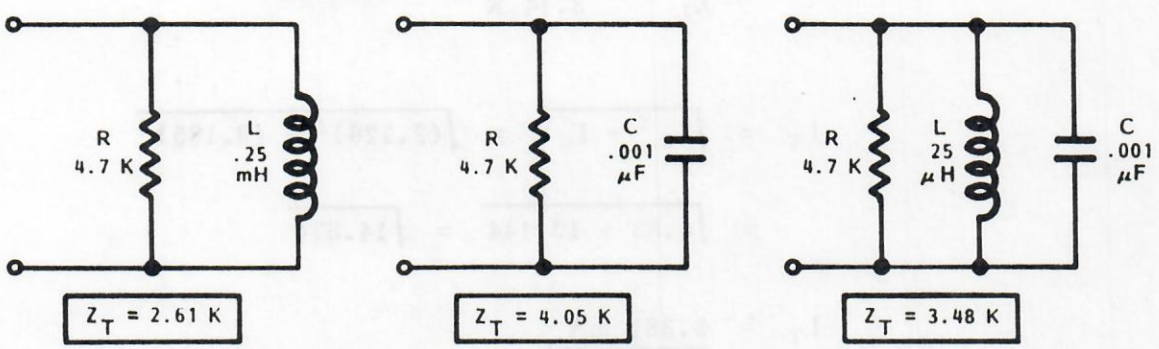


Figure 4 - Three RLC circuit variations and their impedances.

Circuit (a) in Figure 4 will be solved using both methods as follows.

METHOD 1: SINGLE EQUATION

$$Z_T = \sqrt{\frac{(R^2)(X_L{}^2)}{(R^2 + X_L{}^2)}} = \sqrt{\frac{(4.7^2)(3.14^2)}{(4.7^2 + 3.14^2)}}$$

$$= \sqrt{\frac{(22.09)(9.86)}{(22.9 + 9.86)}} = \sqrt{\frac{217.81}{31.95}}$$

$$= \sqrt{6.817}$$

$$\boxed{Z_T = 2.61 \text{ K}}$$

METHOD 2: THREE STEPS

Assume a source voltage of 10 volts.

$$I_R = \frac{V}{R} = \frac{10}{4.7 \text{ K}} = \underline{2.128 \text{ mA}}$$

$$I_L = \frac{V}{X_L} = \frac{10}{3.14 \text{ K}} = \underline{3.185 \text{ mA}}$$

$$I_T = \sqrt{I_R{}^2 + I_C{}^2} = \sqrt{(2.128)^2 + (3.185)^2}$$

$$= \sqrt{4.53 + 10.144} = \sqrt{14.674}$$

$$I_T = \underline{3.381 \text{ mA}}$$

$$Z_T = \frac{V}{I_T} = \frac{10}{3.83 \text{ mA}}$$

$$\boxed{Z_T = 2.61 \text{ K}}$$

The above impedance calculations are valid only at 20 kHz and would have to be redone for any other frequency because both X_L and X_C will vary with frequency. The calculation and verification of the impedances for the circuits in Figures 4(b) and (c) are given as student assignments at the end of this experiment.

In this experiment, you will measure the impedances of a parallel RL, RC and RLC circuit and compare them to the theoretical impedance values given before in Figure 4.

PROCEDURE

1. Wire the circuit shown in Figure 5.

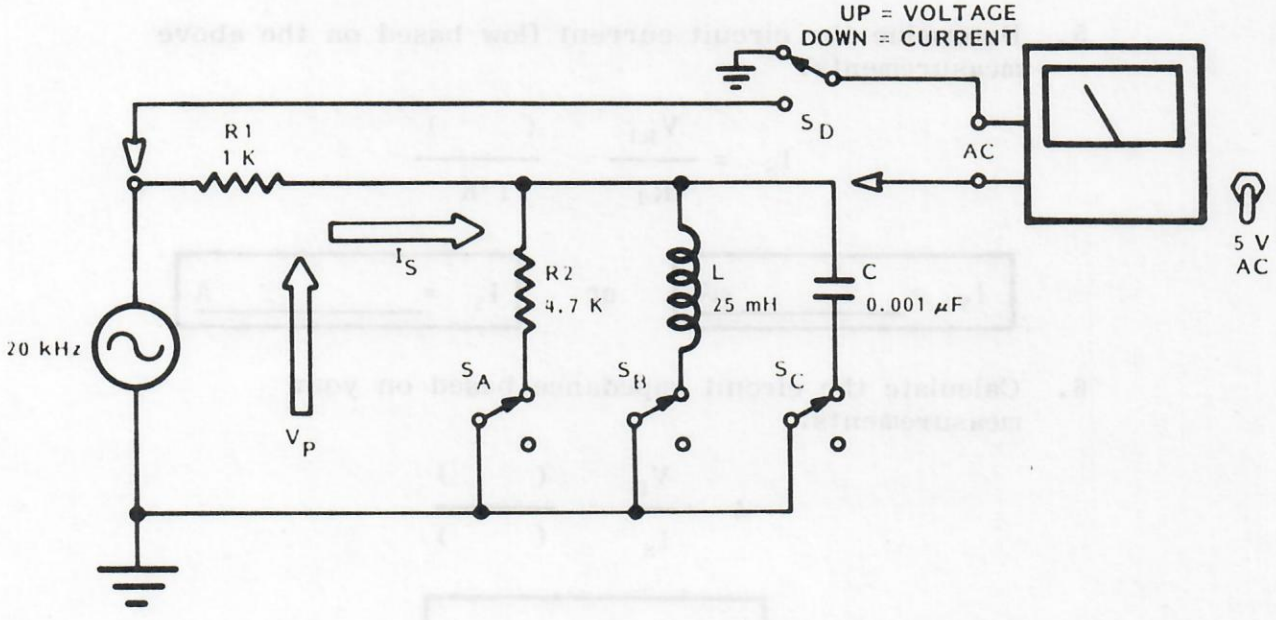


Figure 5 - Parallel RLC circuit and EXPERIMENT.

Switches SA, SB and SC place the R, L and C components in the circuit when the switches are UP. Switch SD permits monitoring of the current when in the DOWN position by measuring the voltage drop across the 1 K series resistor. This voltage reading is equal to the current in milliamperes as in the previous experiments. When switch SD is in the UP position, the meter is measuring V_p, the parallel voltage.

2. Set the Function Generator to 20 kHz.

   Set the input level to maximum.

6.1 RL PARALLEL CIRCUIT IMPEDANCE

3. Set up the RL parallel circuit by setting the switches in the following positions:

FOR R_L NETWORK	SA UP	R
	SB UP	L
	SC DOWN	

4. Read the voltages as follows:

V_P	SD UP	V_P = _____
CURRENT	SD DOWN	V_{R1} = _____

5. Determine the circuit current flow based on the above measurements.

$$I_S = \frac{V_{R1}}{R_1} = \frac{(\quad)}{1\ K}$$

I_S = _____ mA	or	I_S = _____ A

6. Calculate the circuit impedance based on your measurements.

$$Z = \frac{V_P}{I_S} = \frac{(\quad)}{(\quad)}$$

Z = _____ K

How close is the measured impedance to the theoretical value calculated and displayed in Figure 4(a)? _____

_____

To what do you attribute any diferences between the measured and theoretical impedance values? _____

_____

_____

6.2 RC AND RLC CIRCUIT IMPEDANCE

7. The two remaining circuit impedances will now be measured. Set the switches and take the voltage readings for each circuit as directed in Table 1 and enter the readings under the columns marked MEASURE.

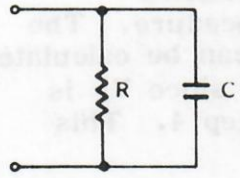
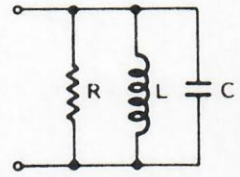
CIRCUIT	SET SWITCHES	MEASURE		CALCULATE	
		V_P SD UP	V_{R1} SD DOWN	$I_S = \frac{V_{R1}}{V_R}$	$Z_P = \frac{V_P}{I_S}$
	A UP B DOWN C UP				
	A UP B UP C UP				

TABLE 1 - RC and RLC circuit measurements.

8. Calculate the circuit current, I_S, for each network. Remember, for a 1 K resistor, I_S, in mA, is directly equal to V_R (SD DOWN). Enter the result in the Table 1 column marked $I_S = V_R$.

9. Calculate the circuit impedance, Z_P, from V_P and I_S and enter the values in the last column, Z_P.

How close are the measured impedance values to the theoretical values presented in Figure 4(b) and (c)?

_____

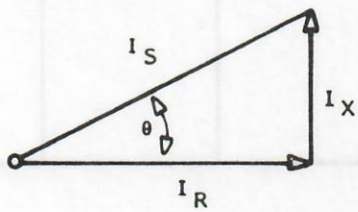
_____

_____

6.3 PHASE ANGLE CALCULATION

10. In a series RLC circuit, it was simple to measure the individual voltage drops around the circuit and then calculate the phase angle. In the parallel RLC circuit, however, all the voltages are the same and the phase angle must be determined using the branch currents. To measure the branch currents requires "breaking" wires, always a difficult problem that is to be avoided.

    Examination of the phasors in Figure 2(b) and Figure 6(a) shows that theta, θ, in a parallel RLC circuit, is the angle between the resistive current, I_R, and the total current, I_S. The value of I_S is known having been measured in step 5 of the procedure. The resistive branch current, I_{R2} (Figure 5), can be calculated quickly and easily using simple Ohm's Law since V_P is known, having been measured earlier in step 4. This is all summarized in Figure 6.



(a) RLC PHASOR

I_S is measured

(b) CURRENTS

$$I_R = \frac{V_P}{R}$$

$$\theta = \text{arc cosine } \frac{I_R}{I_S}$$

(c) θ CALCULATION

Figure 6 - Phase angle calculation in a parallel RLC circuit.

11. Calculate the phase angle for the parallel RLC circuit of Figure 5 as follows:

From step 5 I_S = ( )mA

From step 4 $I_R = \frac{V_P}{R_2} = \frac{(\quad)}{4.7\ K} = (\quad)$mA

Calculate the phase angle, θ, using the arc cosine below:

$$\theta = \text{arc cosine } \frac{I_R}{I_S}$$

$$= \text{arc cosine } \frac{(\quad)}{(\quad)}$$

PHASE ANGLE PARALLEL RLC	θ = _____ °

CONCLUSIONS

We have learned from this experiment that:

The total current in a parallel RLC circuit can be found from:

$$I_T = \sqrt{I_R^2 + (X_L - X_L)^2}$$

The total impedance, Z_T, can be found from:

$$Z_P = \frac{V_P}{I_T}$$

The total impedance may also be found from:

$$Z_P = \sqrt{\frac{1}{\frac{1}{R^2} + \left(\frac{1.}{X_L} - \frac{1}{X_C}\right)^2}}$$

or from:

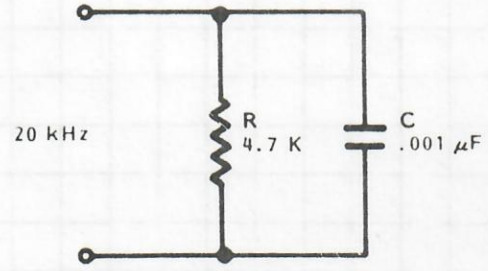
$$Z_P = \sqrt{\frac{(R^2)\ (X_L{}^2)}{(R^2 + X_L{}^2)}}$$

or from:

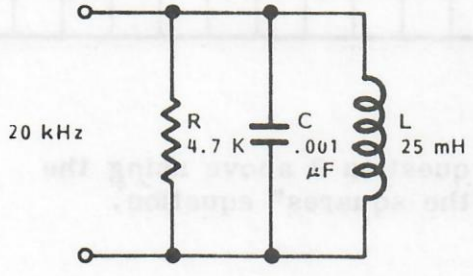
$$Z_P = \frac{(X_C)\ (X_L)}{(X_C - X_L)}$$

ASSIGNMENT

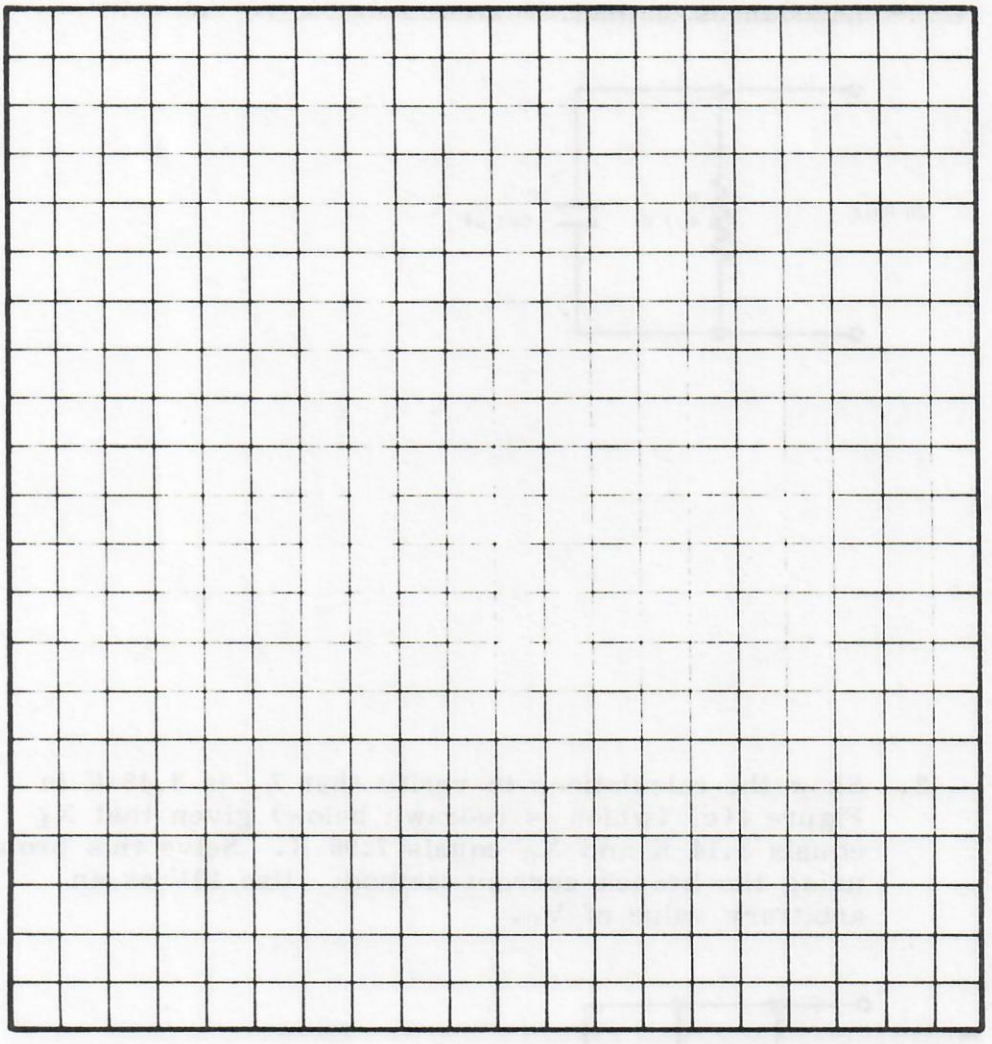
1. Show the calculations to verify that Z_T is 4.05 K in Figure 4(b) (which is redrawn below) given that X_C equals 7.96 K. Solve this problem using the branch impedances method.



2. Show the calculations to verify that Z_T is 3.48 K in Figure 4(c) (which is redrawn below) given that X_L equals 3.14 K and X_C equals 7.96 K. Solve this problem using the branch current method. Use 10V as an arbitrary value of V_P.



3. Construct a phasor diagram on the graph for a parallel RLC circuit and solve for I_S given that I_R = 6 mA, I_L = 4 mA, I_C = 10 mA and V_C = 20 V rms.



4. Solve the problem given in question 3 above using the "square root of the sum of the squares" equation.

5. Given that V_C in problem 3 is 20 volts, find the circuit impedance.

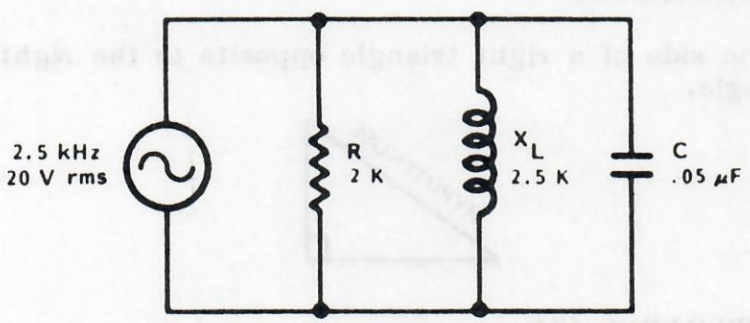


Figure 6 refers to question 6.

6. Solve the following for the circuit of Figure 6 above.

a. X_C

b. I_R

c. I_L

d. I_C

e. I_{X-X}

f. I_T

g. Z

h. θ

KEY TERMS

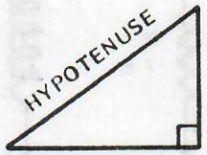
1. CAPACITIVE REACTANCE (X_C)

   The opposition to the flow of ac through a capacitor. It is measured in ohms, indicated as X_C and calculated from

$$X_C = \frac{1}{2\pi fC}$$

2. HYPOTENUSE

   The side of a right triangle opposite to the right angle.



3. IMPEDANCE (Z)

   The resulting total opposition to the flow of ac when resistance, capacitive reactance and inductive reactance are in the circuit. Impedance is defined as Z and is measured in ohms.

4. INDUCTIVE REACTANCE (X_L)

   The opposition to the flow of ac through an inductor. It is measured in ohms, indicated as X_L and calculated from $X_L = 2\pi fL$.

5. LAG

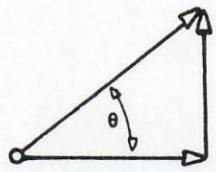
   The difference in time, between two ac signals of the same frequency, measured in degrees between 0 and 360.

6. LEAD

   The opposite of LAG, above. A measurement of the difference in time between two ac signals of the same frequency, measured in degrees.

7. PHASE ANGLE (θ)

The number of degrees by which the current leads or lags the applied voltage. The phase angle is defined by the Greek letter θ. It is shown on a phasor diagram as



8. PHASOR

A phasor, also known as a vector, is used to indicate magnitude and direction as compared to a reference quantity. This is illustrated in 7 above.

9. REACTANCE (X)

Opposition to the flow of ac by an inductor or capacitor. Reactance is measured in ohms and indicated as X (X_C or X_L).

Series Resonance, Bandwidth, Q

INFO SHEET 2

OBJECTIVES

When you finish this information sheet, you will be able to:

1. Define what is meant by resonance.
2. Write the resonance equation and solve for the resonant frequency given the necessary data.
3. Plot a typical resonance curve and identify broad and sharp resonance curves.
4. Calculate the Figure of Merit, Q, of an inductor or tuned circuit.
5. Define Skin Effect and explain how it affects the Q of a coil.
6. Define what is meant by the Half Power Points in a resonant circuit.
7. Calculate and measure the bandwidth of a tuned circuit.

DISCUSSION

Resonant circuits are used in transmitters, receivers and antenna systems. Without resonant circuits, there would be no radio and television operation because resonant circuits are used to determine the frequency of transmission and reception.

SERIES RESONANCE

It has been shown in earlier experiments, that in a series circuit containing both inductive and capacitive reactances, the effective total reactance is their difference. The total impedance is expressed mathematically as:

$$Z = \sqrt{R^2 + (X_L - X_c)^2} \qquad (1)$$

It was also noted earlier that X_L varies directly with frequency and X_C varies inversely with frequency. These relationships are plotted in Figure 1.

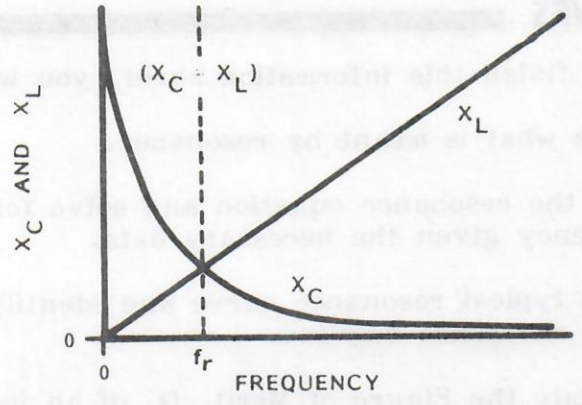


Figure 1 - Plot of X_C and X_L versus frequency.

For any combination of L and C, there is only one frequency at which X_L will equal X_C. This frequency is called the RESONANT FREQUENCY and the condition is known as RESONANCE. The resonant frequency is defined as f_r and, as shown in Figure 1, occurs when $X_L = X_C$.

A typical series RLC circuit is shown in Figure 2. At resonance, X_L cancels X_C and the only opposition (Z) to the flow of current from equation (1), is the resistance, R. The current will thus be greatest at resonance in a series RLC circuit.

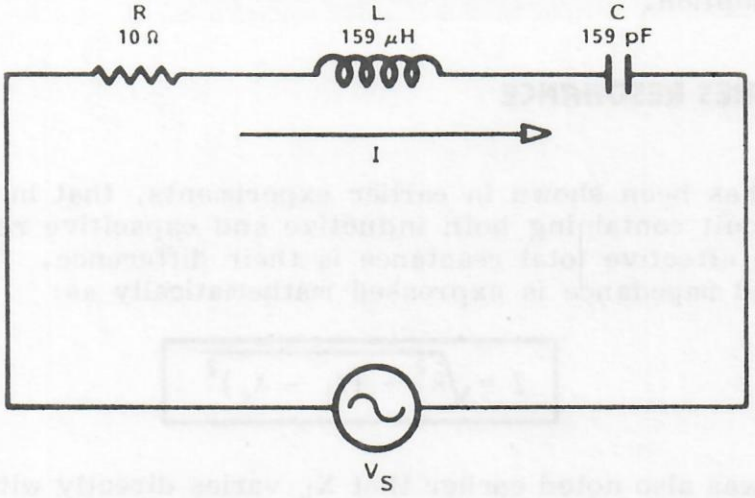


Figure 2 - Series RLC circuit.

This series RLC circuit, at resonance, has the following characteristics:

1. The capacitive reactance equals the inductive reactance.
2. The circuit impedance will be minimum, and equal to the circuit resistance, R.
3. The current flow will be maximum (equal to V_S/R).
4. The series current, I_S, and source voltage, V_S, will be in phase because the circuit is purely resistive.

RESONANCE EQUATION

Because resonance is the condition where X_L equals X_C, the equation used to determine the resonant frequency for any combination of L and C may be developed as follows:

At resonance $$X_L = X_C \tag{2}$$

Expanding by substituting the equations for X_L and X_C, we have:

$$2\pi f_r L = \frac{1}{2\pi f_r C} \tag{3}$$

Transposing:

$$f_r^2 = \frac{1}{4\pi^2 LC} \tag{4}$$

Solving for f_r produces:

RESONANT FREQUENCY EQUATION	$f_r = \dfrac{1}{2\pi\sqrt{LC}}$

(5)

where f_r = resonant frequency in hertz
L = inductance in henries
C = capacitance in farads

As an example, we will solve for the resonant frequency of the series RLC circuit shown in Figure 2.

Given: $R = 10\,\Omega$
$L = 159\ \mu H = 159 \times 10^{-6}\ H$
$C = 159\ pF = 159 \times 10^{-12}\ F$

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{(6.28)\sqrt{(159 \times 10^{-6})(159 \times 10^{-12})}}$$

$$= \frac{1}{6.28\sqrt{25281 \times 10^{-18}}} = \frac{10^9}{1000}$$

$$\boxed{f_r = 1{,}000\ kHz \text{ or } 1\ mHz}$$

RESONANCE CURVES

In Figure 1, capacitive and inductive reactance were plotted against frequency. For a resonant circuit, it is more informative to plot the RLC current and impedance versus frequency. This is shown in Figures 3(a) and (b).

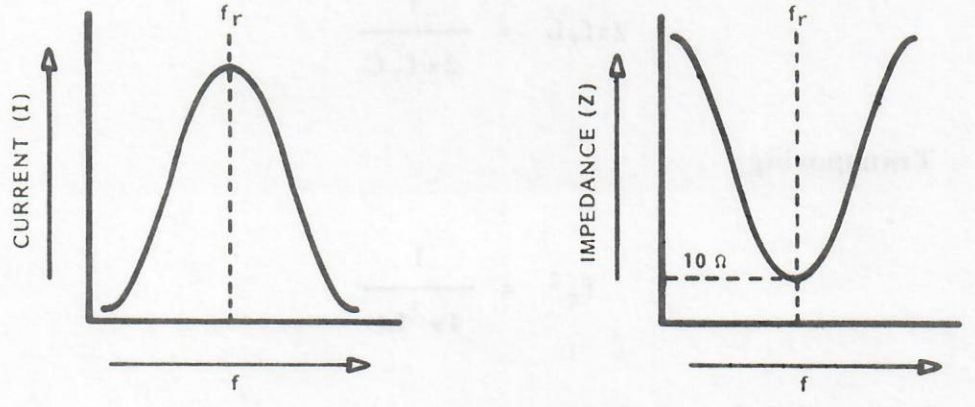


Figure 3 - Frequency response of a series RLC circuit.

The response curves in Figure 3 result from varying the circuit frequency with the applied voltage held constant. The resulting plot is called the RESONANCE CURVE. In curve (a) of Figure 3, the current peaks at resonance where X_C cancels X_L, and the impedance is equal to the series resistance, 10 ohms. The curve of Figure 3(b) shows the impedance, Z, plotted against frequency. At resonance, the impedance is the lowest, equal to the resistance, 10 ohms.

When the circuit resistance is much lower than the circuit reactance, the current decreases rapidly as the frequency is tuned off resonance in either direction because the larger reactances immediately result in a drop in current. The result is a SHARP response curve as in (A) of Figure 4.

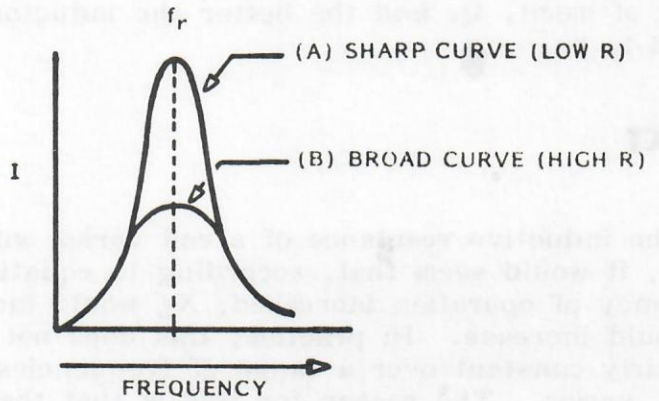


Figure 4 - Sharp and broad resonance curves.

When the circuit resistance is close in value to the reactance values, the RLC circuit current will decrease slowly as the frequency is tuned off resonance in either direction. This is shown in curve (B) of Figure 4 and is called a BROAD response curve.

INDUCTOR QUALITY FACTOR, Q

The QUALITY of an inductor, also called its FIGURE OF MERIT, is identified by the letter Q. The Q of an inductor is equal to the ratio of the energy stored in the magnetic field to the losses generated in the inductor resistance. This is presented mathematically as:

$$Q = \frac{\text{Energy Stored in L}}{\text{Energy Lost in R}} = \frac{I^2 X_L}{I^2 R} \qquad (6)$$

Cancelling I^2, we obtain:

Q FACTOR	$Q = \frac{X_L}{R}$

(7)

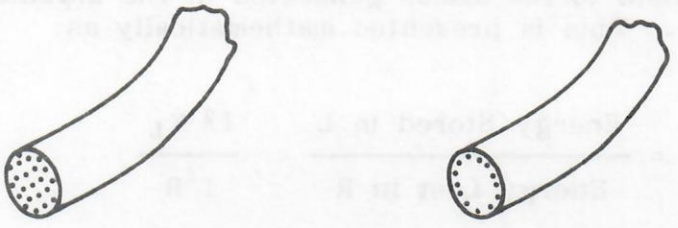
where Q = a number indicating inductor quality
X_L = inductive reactance in ohms
R = inductor resistance or total circuit resistance in ohms

From the preceding, it can be seen that energy lost in the inductor resistance and circuit resistance cannot be stored in the magnetic field because it is dissipated in heat (I^2R) and, therefore, cannot be returned to the circuit. The lower the value of R and the greater value of X_L, the higher the figure of merit, Q, and the better the inductor is considered to be.

SKIN EFFECT

Because the inductive reactance of a coil varies with frequency, it would seem that, according to equation (7), as the frequency of operation increased, X_L would increase and thus Q would increase. In practice, this does not happen. Q remains fairly constant over a range of frequencies even though X_L varies. The reason for this is that the coil resistance is a combination of the dc ohmic resistance (as measured by an ohmmeter) and an ac resistance which is affected by a phenomenon known as SKIN EFFECT.

While dc electron current flow is evenly distributed through the entire cross sectional area of a conductor, the same is not true for ac. As the frequency of the applied voltage is increased, the ac electron current flow tends to move closer to the surface of the inductor wire with few or no electron current carriers flowing in the center of the wire. This effectively reduces the cross sectional area of wire and is known as SKIN EFFECT. This effect increases as the frequency is increased and is shown in Figure 5.



AREA OF CONDUCTION FOR DIRECT CURRENT

AREA OF CONDUCTION FOR ALTERNATING CURRENT

Figure 5 - Cross sectional conduction area for dc and ac.

You will recall that as the cross sectional area of a conductor is reduced, the conductor resistance increases. Thus as the frequency of the voltage applied to an inductor is increased, X_L increases and the effective resistance, R, also increases. This results in a fairly constant value of inductor Q over a wide range of frequencies.

BANDWIDTH

While a series resonant RLC circuit will allow maximum current flow at the resonant frequency, there is also current flow at other frequencies above and below resonance. As the frequency is moved further from resonance, in either direction, the current flow decreases. The range of frequencies, above and below resonance, where the circuit current is high enough to be useful, is defined as the BANDWIDTH, abbreviated BW.

Any frequency that produces a current that generates at least half the power that is generated at resonance is considered to be strong enough to be useful. Any frequencies that generate less than half power are considered too weak to be useful.

This half power point criteria defines the bandwidth. Recall that the formula for power based on a known voltage is:

$$P = \frac{V^2}{R}$$

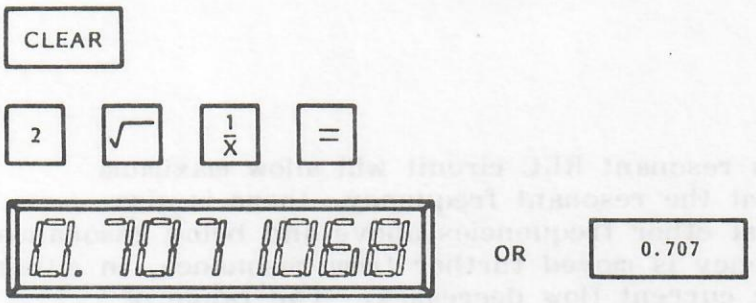
To determine half the power, the equation is:

$$\text{HALF POWER} = \left(\frac{V^2}{R}\right) \times \left(\frac{1}{2}\right)$$

which transposes to:

$$\text{HALF POWER} = \frac{V^2}{2R} = \left(\frac{V}{\sqrt{2}}\right)^2 \times \left(\frac{1}{R}\right) \qquad (8)$$

Thus, when the voltage output of the circuit drops to $V/\sqrt{2}$, the output power level is one half of what it was at reasonance. The value of $1/\sqrt{2}$ is calculated as:



Thus, when the output voltage drops to 0.707 of its value at resonance, the half power point has been reached. Any output below this level is considered outside of the bandwidth of useful signals.

If the resonance curve is plotted as current versus frequency, then the half power points are reached at:

$$\text{Half Power Current Points} = 0.707 \times I_{resonance} \quad (9)$$

If the resonance curve is plotted as voltage versus frequency, the half power points are reached at:

$$\text{Half Power Voltage Points} = 0.707 \times V_{resonance} \quad (10)$$

Those frequencies which produce a current or voltage of at least 70.7% of the resonant value are considered to be strong enough to be useable. The 70.7% points occur above and below resonance at points where $X_C - X_L$ or $X_L - X_C$ equal the circuit resistance.

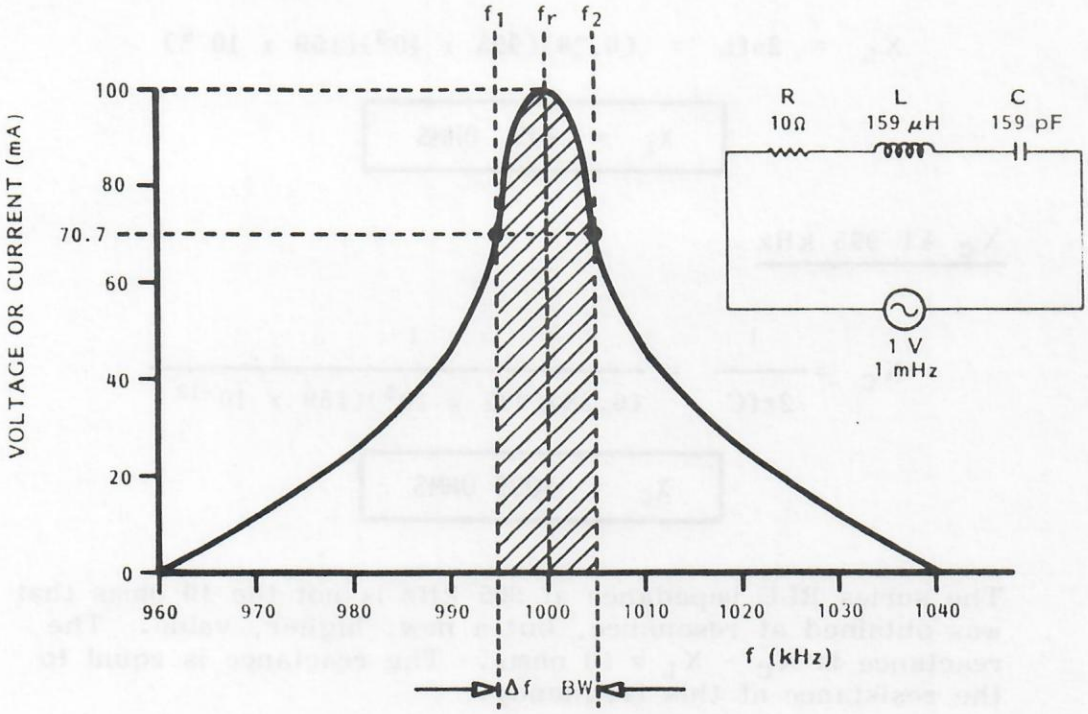


Figure 6 Bandwidth of an LC circuit.

HALF POWER POINT CALCULATIONS

For the resonant circuit shown earlier in Figure 2 and again in Figure 6, the resonant frequency is 1 mHz. With a 1 volt source, at resonance, the current flow is:

$$I_{fr} = \frac{V_S}{R} = \frac{1}{10}$$

$$\boxed{I_{fr} = 0.1 \text{ A or } 100 \text{ mA}}$$

This is shown in the resonance curve of Figure 6 above.

If the input frequency to the series resonant circuit shown in Figure 6 shifts by 5 kHz to 995 kHz, the values of X_L and X_C will change. The new values are shown on the next page.

X_L AT 995 kHz

$$X_L = 2\pi fL = (6.28)(995 \times 10^3)(159 \times 10^{-6})$$

$$\boxed{X_L = 995 \text{ OHMS}}$$

X_C AT 995 kHz

$$X_C = \frac{1}{2\pi fC} = \frac{1}{(6.28)(995 \times 10^3)(159 \times 10^{-12})}$$

$$\boxed{X_C = 1005 \text{ OHMS}}$$

The series RLC impedance at 995 kHz is not the 10 ohms that was obtained at resonance, but a new, higher, value. The reactance is $X_C - X_L = 10$ ohms. The reactance is equal to the resistance at this frequency.

Z AT 995 kHz

$$Z = \sqrt{R^2 + (X_C - X_L)^2} = \sqrt{10^2 + (1005 - 995)^2}$$

$$\boxed{Z = 14.142 \text{ OHMS}}$$

The new RLC circuit current flow at 995 kHz is:

I AT 995 kHz

$$I = \frac{V_S}{Z} = \frac{1}{14.142}$$

$$\boxed{I = 0.0707 \text{ A or } 70.7 \text{ mA}}$$

Thus when $X_C - X_L = R$, this frequency results in a current of 0.707 I or the half power point. If the input frequency is shifted an equal amount above resonance, 1005 kHz, the current flow will be the same, 70.7 mA. Each half of the resonance curve is identical producing a symmetrical curve.

BANDWIDTH CALCULATIONS

The bandwidth of a resonant circuit is that range of frequencies between the two half power points, f_1 and f_2, shown in Figure 6. Expressed mathematically, the bandwidth is:

$$BW = f_2 - f_1 \tag{11}$$

For the resonance curve of Figure 6, the bandwidth is:

$$BW = 1005 - 995$$

$$BW = 10 \text{ kHz}$$

As explained earlier, when the RLC circuit resistance is lower, the resonance curve drops sharply as it goes off resonance. This produces a narrower curve and thus a sharper or narrower bandwidth. Recall from equation (7) that Q is a function of the circuit resistance and now we see that the bandwidth is also affected by the circuit resistance. You may conclude then, that Q affects the bandwith and is related to bandwidth by the equation given below.

$$Q = \frac{f_r}{BW} \tag{12}$$

If the Q of the coil is known, the bandwidth can be determined from:

$$BW = \frac{f_r}{Q} \tag{13}$$

If the inductance of the coil and its resistance are known, the bandwidth can be determined using an equation developed from equations (7) and (12).

$$Q = \frac{X_L}{R}$$

$$Q = \frac{f_r}{BW}$$

Combining, we have:

$$\frac{X_L}{R} = \frac{f_r}{BW}$$

$$BW\ X_L = f_r\ R$$

To solve for BW, transpose X_L yielding:

$$BW = \frac{f_r\ R}{X_L}$$

Expand X_L in terms of L, results in:

$$BW = \frac{f_r\ R}{2\pi f_r L}$$

Cancel f_r results in:

$$\boxed{BW = \frac{R}{2\pi L}} \qquad (14)$$

EXAMPLE

To calculate the Q of the tuned circuit shown in Figure 6 using $Q = X_L/R$, we must first find X_L at resonance, 1 mHz.

$$X_L = 2\pi fL$$

$$= (6.28)(10^6)(159 \times 10^{-6})$$

$$\boxed{X_L = 1000 \text{ OHMS}}$$

Calculating Q:

$$Q = \frac{X_L}{R}$$

$$= \frac{1000}{10}$$

$$\boxed{Q = 100}$$

We can find Q in another way.

$$Q = \frac{f_r}{BW}$$

From our example Figure 6 we find that:

$$Q = \frac{1 \text{ mHz}}{(f_2 - f_1)}$$

$$= \frac{1{,}000 \text{ kHz}}{10 \text{ kHz}}$$

$$\boxed{Q = 100}$$

Bandwidth may be determined when R and L are known.

$$BW = \frac{R}{2\pi L}$$

$$= \frac{10}{(6.28)(159 \times 10^{-6})}$$

$$= \frac{10}{1000 \times 10^{-6}}$$

$$\boxed{BW = 10 \text{ kHz}}$$

These calculations show that many equations can be used to calculate the Q and bandwidth of resonant circuits.

CONCLUSIONS

We have learned from this experiment that:

In a series RLC circuit, resonance occurs when X_L is equal to X_C.

At resonance, a series RLC circuit has a minimum impedance, equal to the circuit dc resistance.

The current flow in a series RLC circuit is maximum at resonance.

At resonance, the current in a series RLC circuit will be in-phase with the voltage source.

The resonant frequency can be calculated from:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The Quality Factor, called Q, in a series resonant circuit is determined by:

$$Q = \frac{X_L}{R}$$

The greater the value of Q, the better the coil quality.

As Q is increased, the resonance curve of the tuned circuit is sharper.

The Q can be defined for a coil, and a different Q value can be calculated for the circuit.

A low Q coil produces a broad response curve in a resonant circuit.

The resistance of a coil, as seen by an ac current, is a combination of the dc resistance of the coil wire plus the ac resistance of the wire caused by skin effect.

When ac flows through a wire, the current carriers move away from the wire center and flow near the skin thus effectively increasing the wire resistance.

Skin Effect becomes more pronounced as the frequency increases.

The resonant circuit bandwidth is measured between the two half power points.

The half power points occur when E or I in the resonant circuit drop to 0.707 of the maximum value found at resonance.

The half power points are equal to:

$$\text{Half Power Current Point} = 0.707 \times I_{resonance}$$

$$\text{Half Power Voltage Point} = 0.707 \times V_{resonance}$$

Bandwidth is the range of frequencies between the two half power points, f_1 and f_2.

$$BW = f_2 - f_1$$

Bandwidth and Q are related. The higher the Q, the narrower the bandwidth.

$$BW = \frac{f_r}{Q}$$

Bandwidth can also be found from:

$$BW = \frac{R}{2\pi L}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. A series resonant circuit is at resonance when:

   a. $X_L = L_R$.
   b. $X_C = R$.
   b. $X_C = X_L$.
   c. all of the above.

2. At resonance in a series resonant circuit:

   a. I is at maximum.
   b. Z is at a minimum.
   c. V_S and I are in phase.
   d. all of the above.

3. The resonance equation is:

   a. $1/\sqrt{LC}$.
   b. $1/\sqrt{2\pi LC}$.
   c. $1/2\pi\sqrt{LC}$.
   d. none of the above.

4. A series resonant circuit is made up of a 100 μH inductor and a 0.005 μF capacitor. Its resonant frequency is closest to:

   a. 225.2 kHz.
   b. 564.3 kHz.
   c. 1.4 mHz.
   d. none of the above.

5. In a series RLC circuit, the resonance curve is:

   a. sharp if R is high.
   b. sharp if R is low.
   c. broad if R is low.
   d. independent of R.

6. If a series RLC circuit that is resonant to 100 kHz, has a capacitive reactance of 1000 ohms and a resistance of 50 ohms, the quality factor is:

   a. 10.
   b. 20.
   c. 100.
   d. insufficient data to compute.

7. Skin effect in an inductor is the greatest when the:

   a. operating frequency is lowest.
   b. circuit resistance is highest.
   c. operating frequency is highest.
   d. circuit resistance is lowest.

8. The bandwidth of a resonant circuit is:

   a. equal to $f_r \times 2$.
   b. equal to $f_r \div 2$.
   c. measured between the half power points on the current curve.
   d. measured at mid-impedance on the impedance curve.

9. A half power point is reached when:

   a. I equals $0.707 \times I_{max}$.
   b. V equals $0.707 \times$ V max.
   c. $X_C = R$.
   d. all of the above.

10. The bandwidth of a series resonant circuit is equal to:

   a. f_r/Q.
   b. $f_r R/X_L$.
   c. $f_2 - f_1$.
   d. all of the above.

KEY TERMS

1. BANDWIDTH

   The range of frequencies between the half power points of the tuned circuit response curve that are passed through. It is expressed as BP = $f_2 - f_1$.

2. FIGURE OF MERIT (Q)

   The Figure of Merit of an inductor is equal to the ratio of the energy stored in the inductor's magnetic field to the energy dissipated by the inductor's resistance. Q has no unit, only a number.

3. HALF POWER POINTS

   The frequencies at which the output power of the tuned circuit drops to one half of the maximum power output. If the output voltage is measured, the half power point occurs when the output voltage drops to 70.7% of the maximum voltage.

4. Q

   See Number 2, Figure of Merit.

5. RESONANCE

   The state that exists in a series circuit consisting of an ac voltage source, capacitance and inductance, when the frequency is such that X_L equals X_C.

6. RESONANCE CURVE

   A graphic plot of frequency versus voltage, current or impedance of a series resonant LC circuit. The normal response is called a BELL CURVE.

7. RESONANT FREQUENCY

   The frequency at which X_L equals X_C in an LC circuit.

8. SERIES RESONANCE

   The state that exists in a series circuit consisting of an ac voltage source, capacitance and inductance, when the frequency is such that X_C equals X_L. The two reactances cancel and the circuit impedance is equal to the resistance of the inductor.

9. SKIN EFFECT

   The tendency of ac currents to flow near the surface of a conductor. This reduces the effective cross sectional area of the conductor causing an increase in resistance.

Series Resonant Circuits 7

OBJECTIVES

When you finish this experiment, you will be able to:

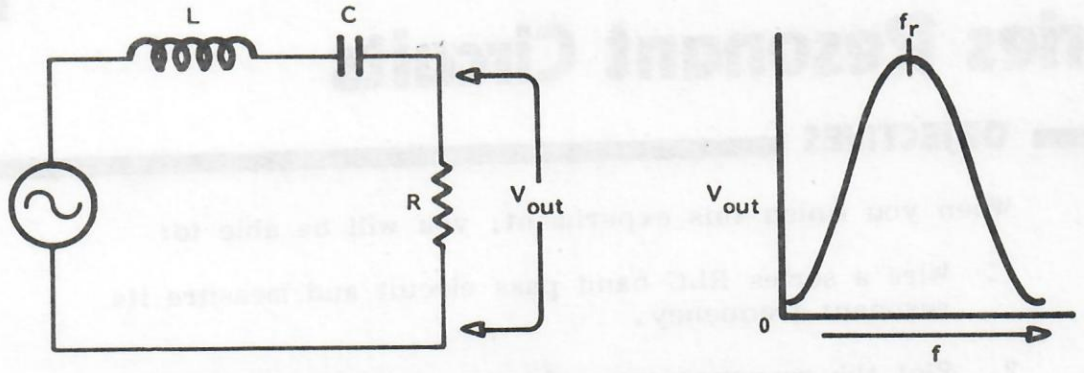
1. Wire a series RLC band pass circuit and measure its resonant frequency.
2. Plot the response curve for the series RLC circuit.
3. Determine the half power points of the circuit.
4. Measure the series RLC circuit bandwidth.
5. Measure the circuit Q.
6. Wire a series RLC band stop circuit.
7. Measure the resonant frequency, bandwidth and Q of the band stop circuit.

DESCRIPTION

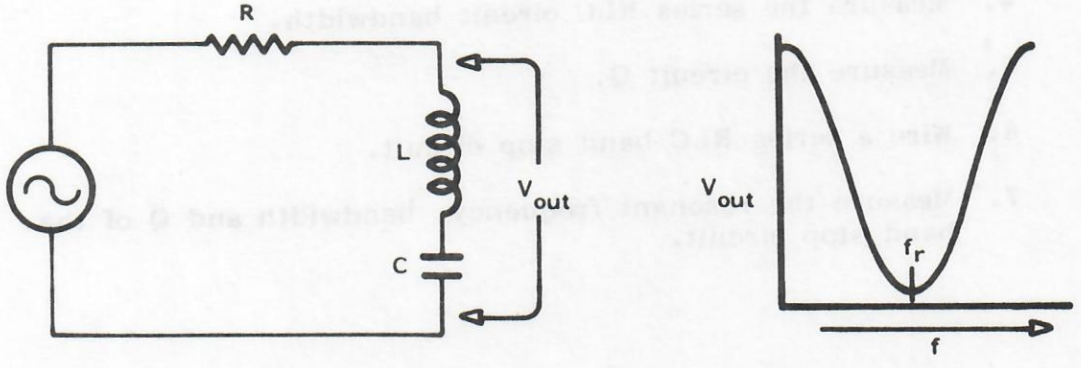
In the previous experiment involving series RLC circuits, it was observed that the voltages across L and C were in opposite phases. The result was a subtraction between the two voltages. When X_C is exactly equal to X_L, the voltages cancel each other and the current flow in the circuit is limited only by the resistance, R. This condition, when X_C equals X_L, is known as RESONANCE.

AT RESONANCE	$X_L = X_C$

Two series RLC circuits are shown in Figure 1. In the circuit of Figure 1(a), the output is taken across the resistor and is maximum at resonance as shown by the accompanying resonance curve.



(a) Series RLC circuit with maximum V_{out} at resonance.



(b) Series RLC circuit with minimum V_{out} at resonance.

Figure 1 - Series resonant RLC circuits.

In Figure 1(b), the output taken across L and C will be zero at resonance because the two voltages across L and C are equal at resonance and also 180° out of phase and they cancel each other.

The resonant frequency of both circuits is calculated from:

$$X_L = X_C$$

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

RESONANT FREQUENCY	$f_r = \frac{1}{2\pi\sqrt{LC}}$

Note that the resistance does not affect the resonant frequency but will affect the Quality Factor of the circuit, Q.

RESONANCE CALCULATIONS

For L = 50 mH and C = 0.01 μF, the resonant frequency is:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{6.28\sqrt{(50 \times 10^{-3})(0.01 \times 10^{-6})}}$$

$$= \frac{1}{6.28\sqrt{5 \times 10^{-10}}}$$

$$= \frac{10^5}{(6.28)(2.24)}$$

$$\boxed{f_r = 7{,}121 \text{ Hz}}$$

HALF POWER POINTS

The useable output signals from the RLC circuit are defined as those frequencies that fall between the half power points on the resonance curve as shown in Figure 2. The half power points occur where the output voltage from the tuned circuit drops to 0.707 times the maximum voltage at resonance as explained earlier in Information Sheet 2. Thus, for the response curve shown in Figure 2, the half power points will occur when the output voltages drops to:

$$\text{Half Power Voltage} = V_{max} \times 0.707$$

$$= (10)(0.707)$$

$$\boxed{\text{Half Power Voltage} = 7.07 \text{ volts}}$$

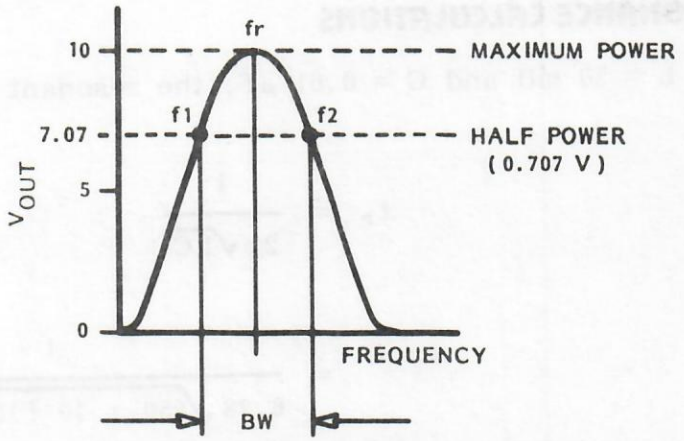


Figure 2 - Resonance curve, half power points and BW.

BANDWIDTH

The BANDWIDTH, BW, is defined as the frequency range between the half power points. This is marked as f_1 for the lower half power point and f_2 for the upper half power point in Figure 2, above. Thus, the bandwidth is equal to:

$$BW = f_2 - f_1$$

The theoretical bandwidth can also be shown to be calculated from the equation:

$$BW = \frac{R}{2\pi L}$$

QUALITY FACTOR (Q)

The QUALITY FACTOR, FIGURE OF MERIT or Q of an inductor, is defined as the ratio of the reactance, X, to the resistance, R. The lower the resistance, R, the higher the inductor quality, Q. This is expressed as:

$$Q = \frac{X_L}{R}$$

The bandwidth and Q are related as explained in Information Sheet 2 and can easily be derived from the above two equations. The higher the Q, the narrower the bandwidth. This may be expressed as:

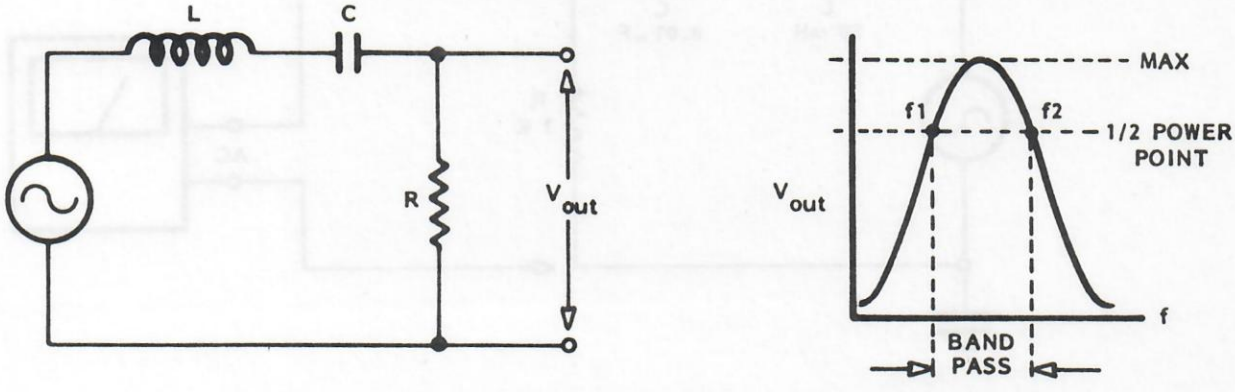
$$BW = \frac{f_r}{Q}$$

and, in another form:

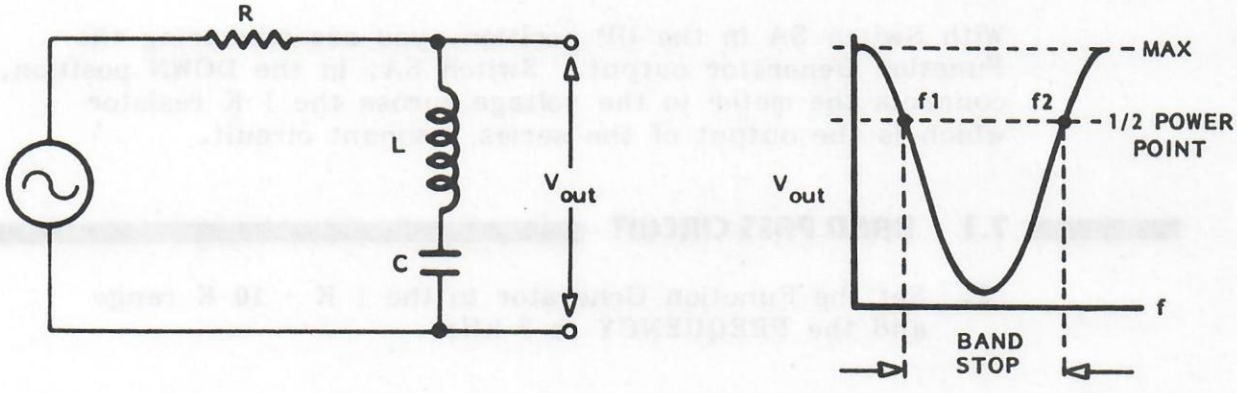
$$Q = \frac{f_r}{BW}$$

BAND PASS AND BAND STOP CIRCUITS

The series RLC circuit can be wired in one of two ways as shown in Figure 3. Figure 3(a) shows what is called a BAND PASS circuit. The output, taken across R, will be maximum at resonance and the circuit will PASS all frequencies between the half power points.



(a) SERIES RLC BAND PASS CIRCUIT



(b) SERIES RLC BAND STOP CIRCUIT

Figure 3 - Band pass and band stop circuits.

For the BAND STOP circuit of Figure 3(b), frequencies between the half power points will be considered to have been stopped. All frequencies below f_1 and all frequencies above f_2 will appear in the output and will be considered to pass through the circuit.

In this experiment, you will wire a series RLC band pass circuit. You will then plot its response curve, measure its resonant frequency, determine the half power points and measure the bandwidth. The Q of the circuit will be measured and an improved circuit Q will be tested by reducing the series resistance. A band stop series RLC circuit will also be tested for resonance.

PROCEDURE

1. Wire the circuit shown in Figure 4.

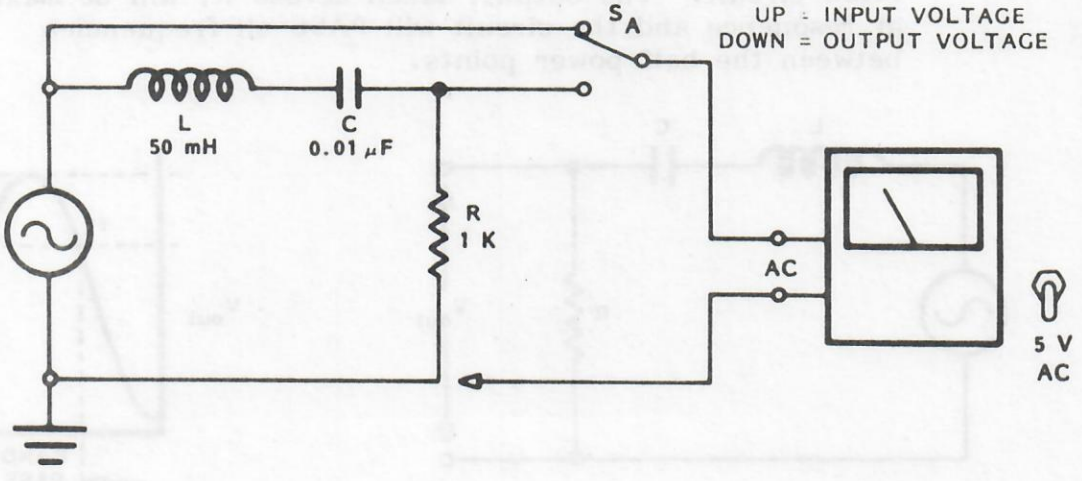


Figure 4 - Series resonant circuit EXPERIMENT.

With Switch SA in the UP position, you are measuring the Function Generator output. Switch SA, in the DOWN position, connects the meter to the voltage across the 1 K resistor which is the output of the series resonant circuit.

7.1 BAND PASS CIRCUIT

2. Set the Function Generator to the 1 K - 10 K range and the FREQUENCY to 2 kHz.

Place Switch SA UP and adjust the input level to 3 volts.

3. Set Switch SA DOWN, measure the output voltage across the 1 K resistor and record it in Table 1.

For V_{in} = 3 VOLTS	
f (kHz)	V_{out}
2	
3	
4	
5	
6	
7	
RESONANCE	⇦ ADJUST FOR RESONANCE, MAXIMUM, AND ENTER HERE
8	
9	
10	
12	
14	

TABLE 1 RLC band pass circuit output voltage.

4. Set the Function Generator to each frequency listed in Table 1. With SA UP, set the generator for 3 volts and then set SA DOWN to measure V_{out}. Record each value in Table 1.

5. The RLC circuit will resonate close to 7 kHz as calculated in the description.

Vary the frequency around 7 kHz for maximum output. Record the resonant frequency and the output voltage below and also in Table 1 in step 3.

AT RESONANCE	f_r = _____ kHz	V_{out} _____ V

6. Plot the results from Table 1 on the graph in Figure 5.

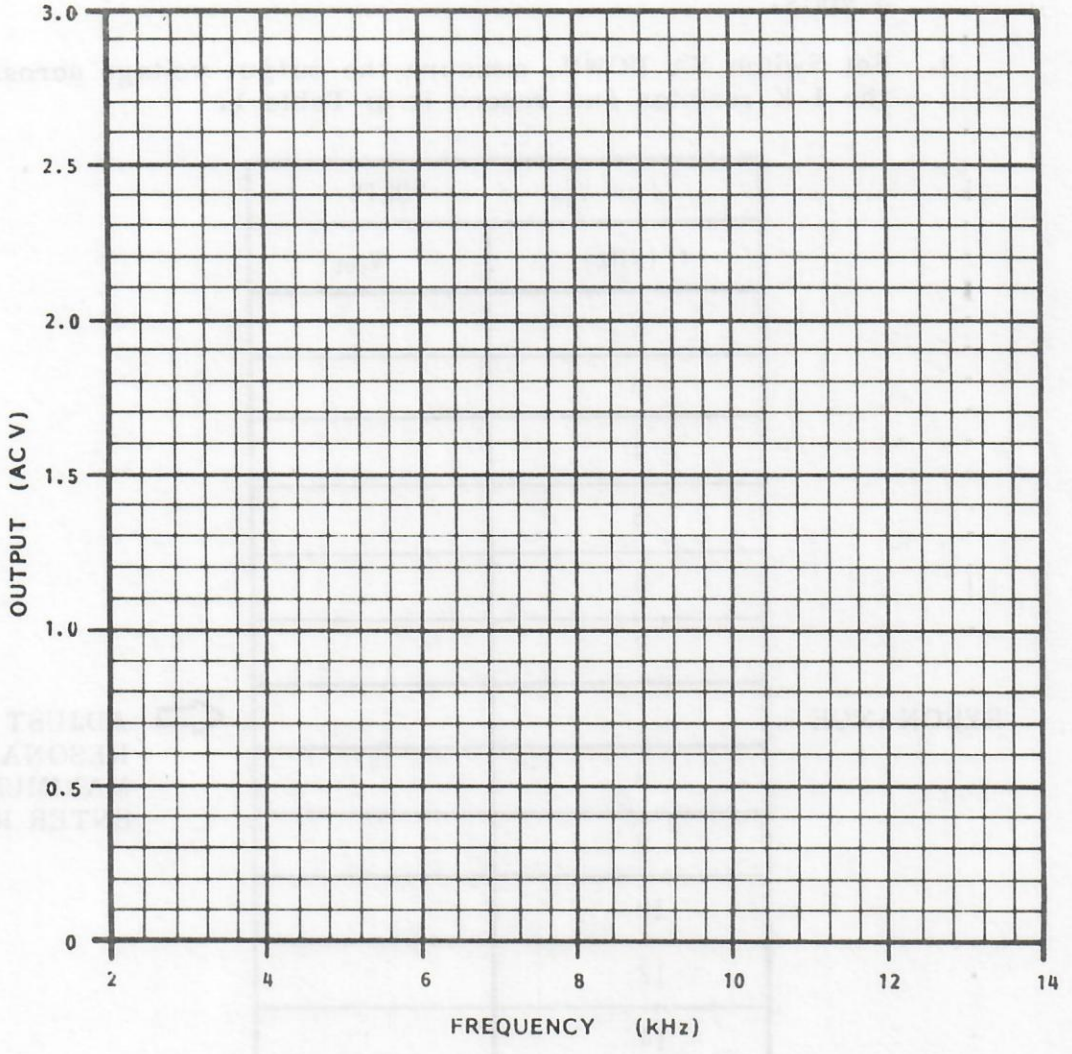


Figure 5 - Plot of V_{out} versus f for the series RLC circuit.

7.2 HALF POWER POINTS AND BANDWIDTH

7. The half power point voltage is given by:

$$V_{half\ power} = (V_{resonance})(0.707)$$

Determine $V_{resonance}$ from Table 1 and substitute it below.

$$V_{half\ power} = (\qquad)(0.707)$$

$V_{half\ power}$ = _____ V

8. Mark the half power voltage on the resonance curve of Figure 5 and draw a horizontal dotted line. The line will appear as shown in Figure 6.

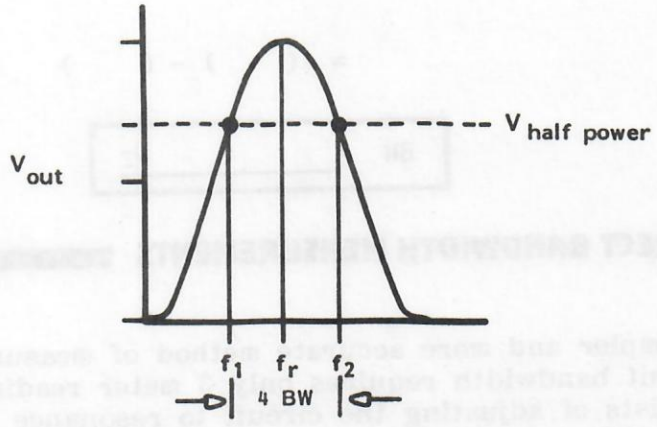


Figure 6 - Bandwith determination.

9. This series resonant circuit tested above passes only a certain range of frequencies and is usually called a:

The WIDTH of this BAND of frequencies is defined as:

BANDWIDTH (BW) is the frequency range over which signals with more than 1/2 the maximum power are transferred to the output.

The lower (f_1) and upper (f_2) frequencies of the band are those frequencies at which the 1/2 power points are reached.

Determine the f_1 and f_2 frequencies at which the half power point line drawn in Figure 5 intercepts the resonance curve.

Enter these high and low cut-off frequencies, f_1 and f_2 below.

f_1 = _____ Hz f_2 = _____ Hz

10. Calculate the Bandwidth, BW, from:

$$BW = f_2 - f_1$$

$$= (\quad) - (\quad)$$

BW = _____ Hz

7.3 DIRECT BANDWIDTH MEASUREMENTS

11. A simpler and more accurate method of measuring the circuit bandwidth requires only 3 meter readings. This consists of adjusting the circuit to resonance and then determining the two frequencies at which the voltage is lower by 0.707 than the resonant output.

    Set Switch SA DOWN to measure the output voltage.

12. Vary the FREQUENCY knob to result in a maximum voltage reading. Record this frequency below.

RESONANT FREQUENCY	f_r = _____ Hz

13. Adjust the SINE AMPL. control so that the circuit output voltage being measured across R is exactly 3 volts.

14. The half power points are at 0.707 x 3 or 2.1 volts.

HALF POWER VOLTAGE	$V_{P/2}$ = 2.1 VOLTS

Vary the frequency above and below resonance until 2.1 volts is reached and enter the frequencies below.

2.1 VOLTS ABOVE f_r	f_2 = _____ Hz

2.1 VOLTS BELOW f_r	f_1 = _____ Hz

15. This measured bandwidth, BW, is now calculated. Insert f_1 and f_2 from above.

$$BW = f_2 - f_1$$

$$= (\quad) - (\quad)$$

BW = _____ Hz

7.4 THEORETICAL BW & QUALITY FACTOR Q

16. The theoretical equation for bandwidth was given in the description as:

$$BW = \frac{R}{2\pi L}$$

The circuit wired from Figure 3 contains a series resistance of 1 K, the 64 ohm dc resistance of the 50 mH inductor and the 100 ohm internal resistance of the Function Generator for a total of 1,164 ohms. Using this data, the theoretical bandwidth is:

$$BW = \frac{1,164}{(6.28)(50 \times 10^{-3})}$$

$$BW = \frac{1,164,000}{(6.28)(50)}$$

CALCULATED THEORETICAL BANDWIDTH	BW = 3,707 Hz

How close is the theoretical BW to the measured BW from step 15?

_____

_____

Q FACTOR COMPARISONS

17. The measured quality factor, Q, can be determined from the experimental data as below.

$$Q = \frac{f_r}{BW}$$

$$Q = \frac{(\qquad)}{(\qquad)} \quad \begin{matrix}\text{(From step 12)} \\ \text{(From step 15)}\end{matrix}$$

MEASURED VALUE	$Q =$ _____

18. Q can also be theoretically calculated from:

$$Q = \frac{X_L}{R}$$

At resonance, 7.2 kHz, the reactance is:

$$X_L = 2\pi fL$$

$$= (6.28)(7.2 \times 10^3)(50 \times 10^{-3})$$

X_L AT RESONANCE	X_L = 2260 OHMS

With a resistance, R, of 1164 ohms, we have:

$$Q = \frac{X_L}{R}$$

$$= \frac{2,260}{1,164}$$

THEORETICAL CALCULATION	Q = 1.94

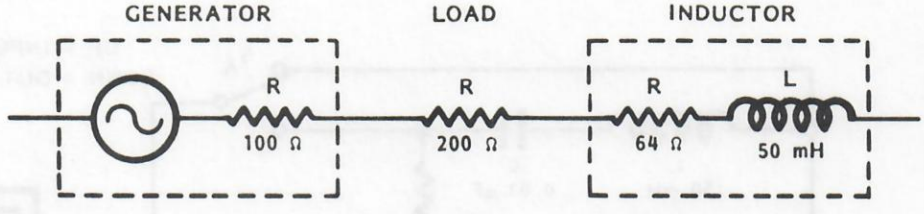
A Q of 1.94 is considered to be low and this low figure is due to the 1K resistor in series with the inductor. The low Q results in a very wide bandwidth and in some applications is perfectly acceptable. If a narrower bandwidth is required, a lower value series resistance must be used.

7.5 IMPROVED CIRCUIT Q

19. The 1 K output resistor in Figure 4 is in series with the internal resistance of the inductor and the circuit quality, that is, the narrowness of the bandwidth, is limited by the 1 K resistance.

    By lowering the series 1 K resistance to 200 ohms, the BW will become narrower, which for some applications is essential. As noted earlier, a series resistance of 200 ohms will load the generator excessively. Most Function Generators have an internal resistance of 600 ohms which limits the Q of the circuit since it is part of the RLC series network. The Ed-Lab Function Generator has a 100 ohm internal resistance. While this will allow an improved circuit Q, it can also permit excessive current drain to distort the output waveshape. To prevent this from happening, we must keep the circuit input voltage low and we will set it at 2 volts.

20. The new series resistance of 200 ohms provides a total resistance, R_T, of:



$$R_T = 364\,\Omega$$

Determine the theoretical Q with 364 ohms, using the equation:

$$Q = \frac{X_L}{R_T}$$

$$= \frac{2260}{364} \qquad \text{(From Step 18)}$$

THEORETICAL Q FOR 364 OHMS	Q = 6.21

21. The theoretical bandwidth is:

$$BW = \frac{R}{2\pi L}$$

$$= \frac{364}{(6.28)(50 \times 10^{-3})}$$

THEORETICAL BANDWIDTH FOR 364 OHMS	BW = 1,159 Hz

EXPERIMENTAL HIGHER Q (OPTIONAL)

22. Wire the circuit shown in Figure 7.

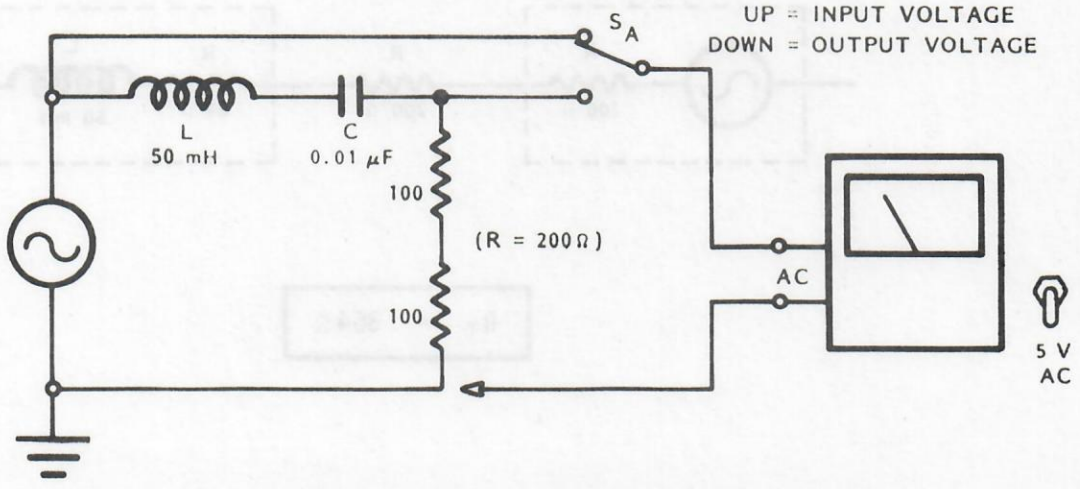


Figure 7 - High circuit Q EXPERIMENT.

23. Set the Function Generator SINE AMPL. control for full output (CW).

Set Switch SA DOWN and adjust the frequency control for maximum output. The resonant frequency should be close to that obtained earlier. Record it below.

MEASURED	f_r = _____ Hz

This resonant frequency is the same as before because L and C are the same.

24. Set Switch SA UP and adjust the input voltage to the circuit to 2 volts.

Set Switch SA DOWN. Read and record the output voltage at resonance.

RESONANT OUTPUT V	V_{out} = _____ V

25. Calculate the half power point voltage from:

$$V_{half\ power} = (V_{resonance})(0.707)$$

$$= (\quad)(0.707)$$

$V_{half\ power}$ = _____ V

26. With SA DOWN, adjust the frequency downward (f_1) until the meter reads the half power point voltage calculated in step 25.

Set SA UP and reset the signal from the Function Generator to 2 volts if it has changed due to loading.

Set SA DOWN and readjust the frequency control for the correct half power voltage.

Repeat this procedure until the two readings (input of 2 volts and the output voltage at the 1/2 power point) remain correct for each position of SA.

Record the f_1 frequency below.

MEASURED LOWER HALF POWER POINT	f_1 = _____ Hz

27. Increase the frequency above resonance until the meter reads the f_2 half power voltage (checking the input voltage the same as for f_1).

Record the f_2 frequency below.

MEASURED UPPER HALF POWER POINT	f_2 = _____ Hz

28. Calculate the measured bandwidth for a total series resistance of 364 ohms.

$$BW = f_2 - f_1$$
$$= (\quad) - (\quad)$$

MEASURED BW WITH 364 Ω RESISTANCE	BW = _____ Hz

Compare the measured BW above to the theoretical BW calculated earlier in step 21. Are the measured and theoretical values close?

_____

_____

Compare the bandwidth for R = 200 ohms to that for R = 1 K.

_____

_____

_____

29. Calculate the new Q from your measurements.

$$Q = \frac{f_r}{BW}$$

$$= \frac{(\quad)\ \text{From Step 23}}{(\quad)\ \text{From Step 28}}$$

MEASURED Q FOR R = 364 Ω	Q = _____

This Q, for a circuit resistance of 364 ohms, should be higher than the previous Q with a circuit resistance of 1164 ohms in the circuit of Figure 4.

Note that the Q being measured is the "Q of the circuit" and not the "Q of the coil."

7.6 BAND STOP CIRCUIT

30. Wire the circuit shown in Figure 8.

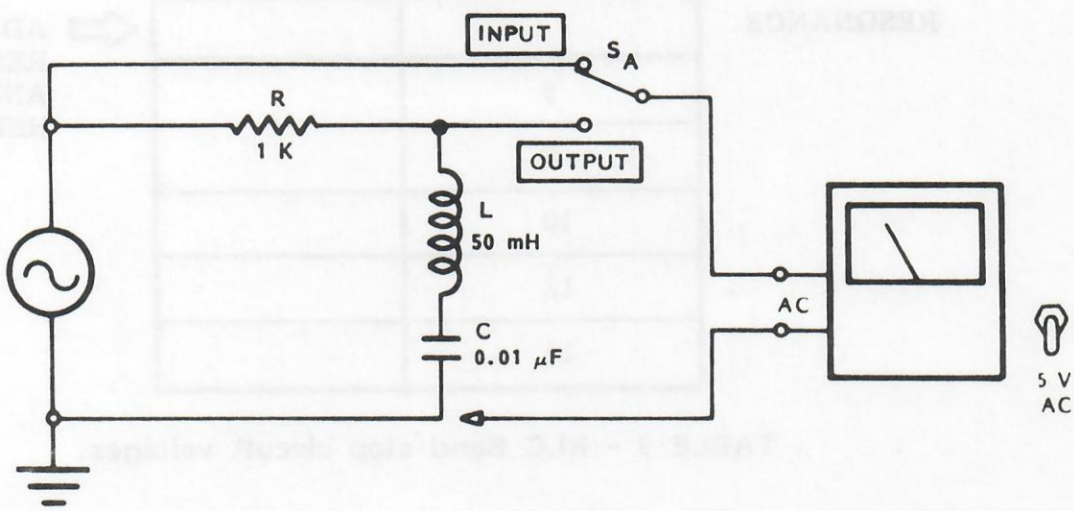


Figure 8 - Band stop circuit EXPERIMENT.

When the circuit of Figure 8 is at resonance, X_L will equal X_C with a resulting zero output reactance. This, in turn, results in a very low output voltage at resonance.

31. Set Switch SA UP to measure the input voltage.

Set the Function Generator frequency at 2 kHz.

Adjust the Function Generator circuit input voltage to 3 volts.

32. Set Switch SA DOWN. Measure and record the output voltage and record it in Table 2.

For V_{in} = 3 VOLTS	
f (kHz)	V_{out}
2	
3	
4	
5	
6	
7	
RESONANCE	⇦ ADJUST FOR RESONANCE, AND ENTER HERE.
8	
9	
10	
12	
14	

TABLE 2 - RLC Band stop circuit voltages.

33. With SA UP, set the Function Generator to 3 volts. Set the Function Generator to each frequency listed in Table 2 and record each output voltage reading (with switch SA DOWN.)

34. Plot the results of Table 2 on the graph of Figure 9.

35. Using the 2.1 volt dashed line already on the graph as the half power point level, determine the BW of the filter.

$$BW = f_2 - f_1$$

$$= (\quad) - (\quad)$$

MEASURED BW OF BANDSTOP CIRCUIT	BW = _____ Hz

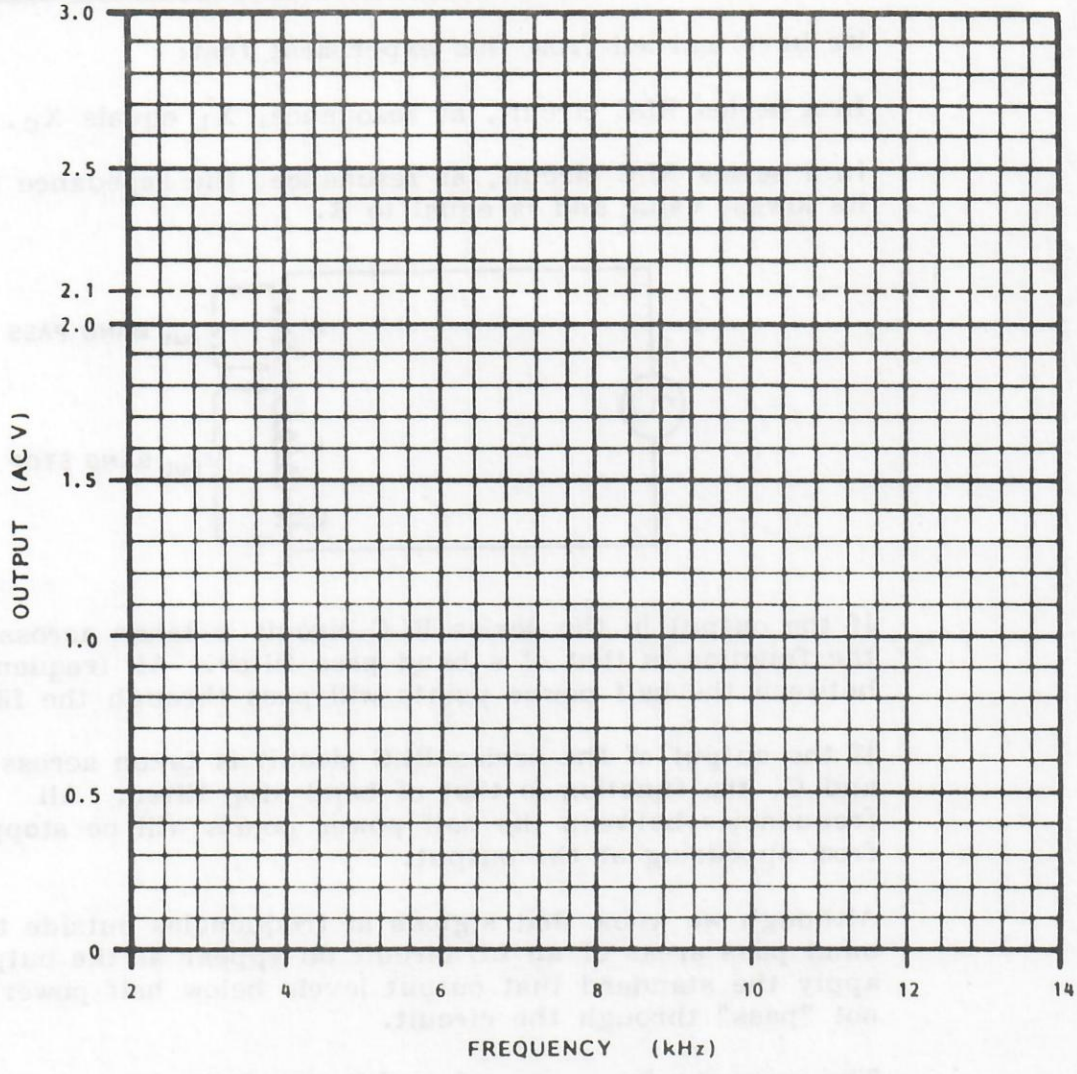


Figure 9 - Graph to plot band stop response curve.

36. Calculate the measured Q of the band stop circuit from:

$$Q = \frac{f_r}{BW}$$

$$= \frac{(\quad)}{(\quad)} \quad \begin{matrix} \text{From step 33, Table 2} \\ \text{From step 35} \end{matrix}$$

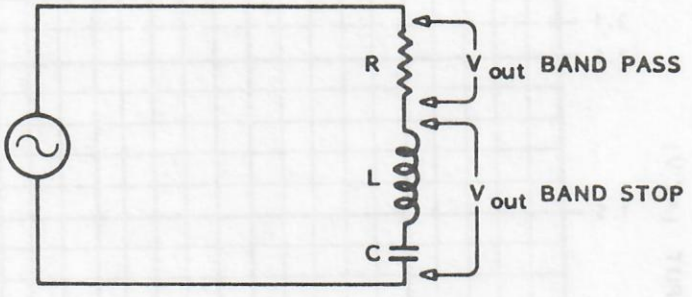
MEASURED BAND STOP CIRCUIT Q	Q = _____

CONCLUSIONS

We have learned from this experiment that:

In a series RLC circuit, at resonance, X_L equals X_C.

In a series RLC circuit, at resonance, the impedance is at its lowest value and is equal to R.



If the output in the series RLC circuit is taken across R, the function is that of a band pass filter. All frequencies between the half power points will pass through the filter.

If the output of the series RLC circuit is taken across L and C, the function is that of band stop filter. All frequencies between the half power points will be stopped from appearing at the output.

Although we know that signals at frequencies outside the band pass areas of an LC circuit do appear at the output, we apply the standard that output levels below half power do not "pass" through the circuit.

The resonant frequency of an LC circuit is determined from:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

To find L or C when the frequency and one component are known, the equations are:

$$L = \frac{1}{4\pi^2 f_r^2} \quad \text{and} \quad C = \frac{1}{4\pi^2 L f_r^2}$$

The half power points are the frequencies above and below resonance where the output voltage drops to 70.7% of the maximum voltage at resonance or half the power developed at resonance.

The bandwidth is that range of frequencies between the half power points, f_1 and f_2.

The bandwidth is calculated from:

$$BW = f_2 - f_1$$

The Quality Factor, Q, of an inductor is determined by:

$$Q = \frac{X_L}{R}$$

The bandwidth of the RLC circuit is related to Q by:

$$BW = \frac{f_r}{Q}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. In a series RLC circuit, at resonance:

   a. $X_L = 2X_C$
   b. $X_C = 2X_L$
   c. $X_L = R$
   d. $X_C = X_L$

2. To produce a band pass response for an RLC series circuit, the output must be taken from across:

   a. R only.
   b. R and L in series.
   c. L and C in series.
   d. R and C in series.

3. To produce a band stop response for an RLC series circuit, the output must be taken from across:

   a. R only.
   b. R and L in series.
   c. L and C in series.
   d. R and C in series.

4. The formula to determine the resonant frequency of an RLC circuit is:

   a. $\dfrac{1}{2\pi\sqrt{RC}}$
   b. $\dfrac{1}{2\pi\sqrt{RL}}$
   c. $\dfrac{1}{4\pi 2\sqrt{LCR}}$
   d. $\dfrac{1}{2\pi\sqrt{CL}}$

5. A 40 mH inductor, 200 $\mu\mu$f capacitor and 50 ohm resistor are wired in series. The resonant frequency of the combination will be closest to:

   a. 56.27 kHz.
   b. 56.27 mHz.
   c. 50.35 kHz.
   d. 8.108 mHz.

6. The bandwidth of a resonant circuit is measured between the:

   a. 70.7% points.
   b. 0.707 points.
   c. half power points.
   d. any or all of the above.

7. The f_1 and f_2 frequencies of a resonant circuit are measured at f_1 = 2.1 mHz and f_2 = 2.6 mHz. The bandwidth is:

   a. 4.7 mHz.
   b. 5.46 mHz.
   c. 0.5 kHz.
   d. 0.5 mHz.

8. The inductor in an RLC series resonant circuit is 50 mH, the capacitor 0.002 μF and the total circuit resistance is 100 ohms. The circuit bandwidth is closest to:

   a. 49.9 Hz.
   b. 318.47 Hz.
   c. 15.923 kHz.
   d. none of the above.

9. A series RLC circuit is resonant at 100 kHz. The inductor is 30 mH and the total circuit resistance is 50 ohms. THe circuit Q is closest to:

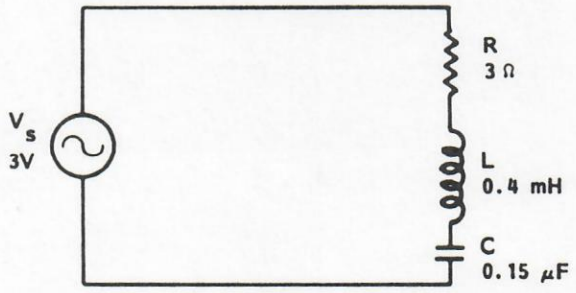
   a. 1.66
   b. 20
   c. 60
   d. 75.36

10. The peak output power, at resonance, for a circuit is 0.006 watts. The half power point frequency level will be at:

   a. 0.003 watts.
   b. 0.0042 watts.
   c. $(0.006)(\sqrt{2})$ or 0.0085 watts.
   d. none of the above.

PROBLEMS

11. For the circuit shown, calculate the resonant frequency and their solve for those quantities listed below, at resonance. Show all work.



   a. f_r

b. X_C

c. X_L

d. Z

e. I_T

f. Q

g. BW

h. f_1

i. f_2

KEY TERMS

1. BAND PASS

   The range of frequencies between the half power points of the tuned circuit response curve. It is expressed as $BP = f_2 - f_1$.

2. BAND PASS CIRCUIT

   Also called a band pass filter, this circuit passes a band of frequencies ($f_2 - f_1$) and blocks all frequencies above f_2 and all frequencies below f_1.

3. BANDWIDTH

   The range of frequencies of a tuned circuit that fall between the half power points. It is expressed as $BW = f_2 - f_1$.

4. HALF POWER POINTS

   The frequencies on a frequency versus output power graph, where the power level drops to one half. If calibrated in frequency versus voltage, the half power points exist where the voltage drops to 70.7% of the maximum value.

5. Q

   The Q of an inductor, also called the Quality Factor or Figure of Merit, is equal to the ratio of the inductor's reactance, X_L, and its resistance R. Thus, $Q = X_L/R$.

6. RESONANCE

   A condition in an LC circuit where X_L equals X_C. Resonance occurs at one frequency only, and the resonant frequency, f_r, is determined from

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

7. RESONANCE CURVE

   A plot of frequency versus voltage or current or impedance, of an LC circuit. The normal response is called a Bell Curve.

8. RESONANT FREQUENCY

   The frequency at which X_L equals X_C in an LC circuit.

9. RESPONSE CURVE

A plot of voltage, or current, or impedance versus frequency for an LC circuit.

10. SERIES RESONANCE

The state that exists in a series circuit consisting of an ac voltage source, capacitance, inductance and resistance when the frequency is such that X_L equals X_C.

Series RLC Circuit Voltages 8

OBJECTIVES

When you finish this experiment, you will be able to:

1. Calculate and measure the resonant frequency of a series RLC circuit.
2. Calculate the current flow in a series RLC circuit.
3. Measure the voltage distribution in a series RLC circuit.
4. Verify the voltage magnification that occurs in a series RLC circuit.
5. Write three different equations that can be used to calculate Q.
6. Calculate and measure the Q of a series RLC circuit.
7. Demonstrate the phase angles in an RLC circuit at resonance and above and below resonance.

DESCRIPTION

The series resonant RLC circuit was studied earlier in Information Sheet 2 and Experiment 7 and the resonant frequency calculations, the impedance at resonance and the current and voltage distribution were covered. This experiment demonstrates another interesting aspect of the series RLC circuit, VOLTAGE MAGNIFICATION, which will be examined by measuring the circuit voltages. The circuit to be studied and the component values are given in Figure 1.

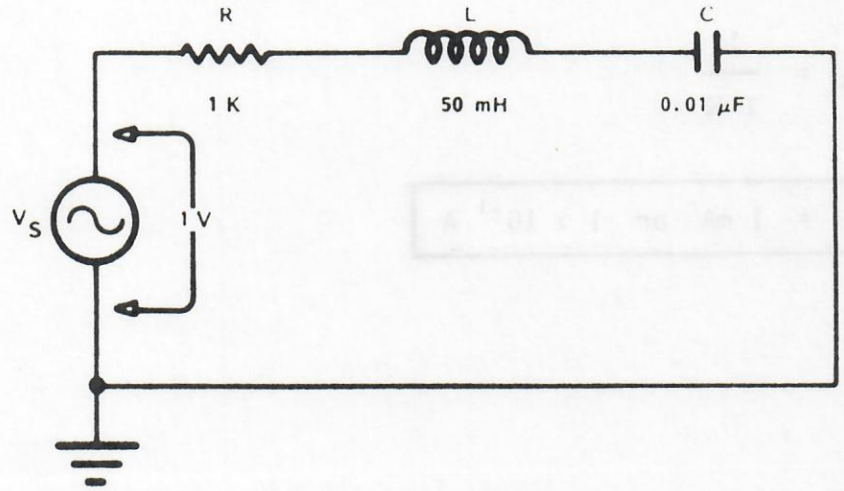


Figure 1 - Series RLC circuit.

RESONANT FREQUENCY

The resonant frequency for the circuit of Figure 1 is:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

$$= \frac{1}{6.28\sqrt{(50 \times 10^{-3})(0.01 \times 10^{-6})}} = \frac{1}{6.28\sqrt{0.5 \times 10^{-9}}}$$

$$= \frac{10^6}{(6.28)(22.3)}$$

$$\boxed{f_r = 7{,}140 \text{ Hz}}$$

SERIES CURRENT

At resonance, X_L equals X_C and cancel each other and the current is determined by the input voltages, V_S, (which is to be set at 1.0 volt) and the 1 K series resistance. The current is given by Ohm's Law as:

$$I_S = \frac{E}{R}$$

$$I_S = \frac{1}{1\text{ K}}$$

$$\boxed{I_S = 1 \text{ mA or } 1 \times 10^{-3} \text{ A}}$$

INDUCTOR VOLTAGE DROP

The reactance of the inductor at resonance (7.14 kHz) is given by:

$$X_L = 2\pi fL \qquad (2)$$

$$= (6.28)(7.14 \times 10^3)(50 \times 10^{-3}) = (6.28)(357)$$

INDUCTOR REACTANCE	X_L = 2,242 OHMS

The voltage across the inductor (V_L), at resonance, is given by Ohm's Law and is:

$$E = I\,R$$

or

$$V_L = I_S\,X_L$$

$$= (1 \times 10^{-3})(2,242)$$

THEORETICAL INDUCTOR VOLTAGE	V_L = 2.242 VOLTS

Observe that the voltage across the inductor, V_L, is 2.242 volts while the applied voltage, V_S, is ONLY 1 VOLT. This is called VOLTAGE MAGNIFICATION.

CAPACITOR VOLTAGE DROP

The capacitor voltage drop (V_C) will also be 2.242 volts at the resonant frequency because X_C equals X_L and the same I_S also flows through X_C.

VOLTAGE MAGNIFICATION DEPENDS ON Q

The amount of voltage magnification is a function of the circuit Q. The higher the circuit Q, the greater the voltage magnification. The Q in a series circuit depends on the sum of the inductor resistance and the external series resistor. Q can be defined as the ratio of inductor power dissipation to resistor power dissipation.

$$Q = \frac{P_{XL}}{P_R} \tag{3}$$

By substituting voltage times current as equivalent to power, we have:

$$Q = \frac{V_L\ I_L}{V_R\ I_R} \tag{4}$$

Because this is a series circuit, I_L and I_R are equal and therefore can be cancelled so that:

$$Q = \frac{V_L}{V_R} \tag{5}$$

Because, at resonance, V_L and V_C cancel, the source voltage, V_S, appears across R. Thus, $V_S = V_R$ and equation (5) can be written as:

$$Q = \frac{V_L}{V_S} \tag{6}$$

Equation 6 can be rearranged so that:

$$V_L = Q\ V_S \tag{7}$$

Thus, at resonance, the voltage across the inductor, V_L, is Q times the source voltage, V_S.

The theoretical Q for the circuit of Figure 1 is given by:

$$Q = \frac{X_L}{R} \tag{8}$$

The reactance, X_L, was calculated earlier as 2,242 ohms and Figure 1 shows R to be 1 K. Thus:

$$Q = \frac{2242}{1000}$$

THEORETICAL FIGURE OF MERIT (QUALITY FACTOR)	$Q = 2.242$

Using equation (7), V_L can be determined as:

$$V_L = Q\ V_S$$

$$= (2.242)(1)$$

THEORETICAL INDUCTOR VOLTAGE BASED ON Q	$V_L = 2.242$ VOLTS

This value of V_L, based on Q, corresponds exactly to the theoretical value calculated earlier using X_L and Ohm's Law.

In this experiment, you will first observe the voltage magnification off-resonance and then at-resonance. You will measure the circuit Q based on voltages and compare it to the theoretical Q. The phases and amplitudes of V_L and V_C will be observed on an oscilloscope and then the phase angle between V_S and I_T will be observed at resonance and above and below resonance as well.

PROCEDURE

1. Wire the circuit shown in Figure 2.

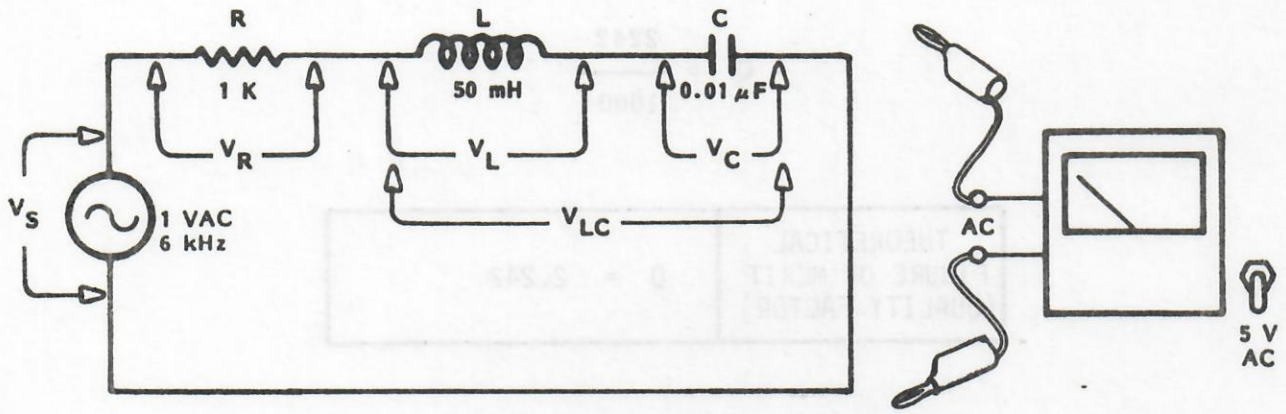


Figure 2 - Series RLC circuit EXPERIMENT.

8.1 VOLTAGE MEASUREMENTS

2. Set the Function Generator frequency off-resonance at 6 kHz.

3. Connect the meter leads across the generator and adjust the voltage to 1 volt.

4. Measure all the voltage drops in the series circuit and enter them in Table 1.

V_S	1	V
V_R		V
V_L		V
V_C		V

TABLE 1 - Voltage distribution in series RLC circuit.

5. Are the reactive voltages, V_L and V_C, greater than V_S?

Observe that, unlike Kirchhoff's Voltage Law in dc circuits, you cannot add $V_R + V_L + V_C$ to obtain V_S. It is necessary to use phasor diagrams or the equation for the right triangle to add the voltages. Recall that V_L and V_C are 180° out of phase with each other and thus cancel.

6. Measure the voltage across the L and C combination (V_{LC} as marked in Figure 2) using the meter and enter the reading below.

MEASURED V_{LC}	V_{LC} = _____ V

7. Subtract V_L from V_C as listed in Table 1 and compare the result to the V_{LC} voltage reading taken in step 6.

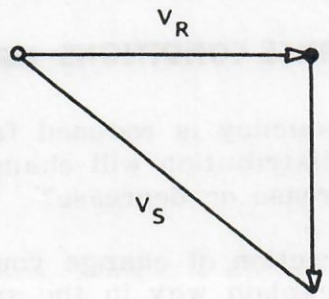
$$V_{LC} = V_C - V_L$$

$$V_{LC} = (\quad) - (\quad)$$

$$V_{LC} = \_\_\_\_\_ V$$

Are the results close in value? _____

8. Calculate the source voltage, V_S, from:



where V_R, V_C and V_L are taken from Table 1.

$$V_S = \sqrt{V_R^2 + (V_C - V_L)^2}$$

$$= \sqrt{(\quad)^2 + [(\quad) - (\quad)]^2}$$

$$V_S = \sqrt{(\quad) + (\quad)}$$

$$V_S = \_\_\_\_\_ V$$

How does the calculated V_S above compare to the measured 1 volt set in step 3?

_____

_____

8.2 MEASUREMENTS AT RESONANCE

9. Connect the ac meter across the L and C combination again to measure the voltage, V_{LC}.

Adjust the Function Generator frequency to resonance as indicated by the minimum reading of V_{LC}. The voltage reading will not indicate zero because of the inductor's dc resistance of 64 ohms.

Record the minimum V_{LC} voltage reading and the resonant frequency below.

V AND F AT RESONANCE AS MEASURED BY MINIMUM V_{LC}	V_{LC} = _____ V
	f_r = _____ kHz

How close is the measured f_r to the calculated f_r in the description? _____

_____

_____

8.3 OFF-RESONANCE CONDITIONS

10. When the frequency is reduced from resonance to 5 kHz, the voltage distribution will change. Will V_R, V_L, V_C and V_{LC} increase or decrease?

Enter the direction of change you would expect for each voltage and explain why in the space provided.

AS f IS REDUCED FROM RESONANCE -	
UP OR DOWN	REASON
V_R _____	_____
	_____
	_____
V_L _____	_____
	_____
	_____

V_C _____ _____

_____

_____

V_{LC} _____ _____

_____

_____

11. Set the Function Generator to 5 kHz.

    Check V_S to be certain it is still set at 1 volt.

12. Read all the circuit voltages and enter them in Table 2.

V_S	1 V
V_R	V
V_L	V
V_C	V
V_{LC}	V

TABLE 2 - Voltage distribution at 5 kHz.

Have the voltages changed as you expected them to? _____

_____

_____

8.4 Q MEASUREMENTS (OPTIONAL)

13. The resonant frequency of the series RLC circuit can be measured in a number of ways. You have already adjusted the frequency for a minimum reading across L and C (V_{LC}.) It is also possible to adjust the frequency to resonance by varying the frequency for a maximum current indicated by a maximum voltage across R.

Connect the ac meter across R. Vary the frequency until the voltage reaches maximum. Record the voltage reading and the resonant frequency below:

V_R and f_r AT RESONANCE AS MEASURED BY MAXIMUM I	V_R = _____ V
	f_r = _____ kHz

14. With the circuit at resonance, use the ac meter and read V_S and V_L and enter the results below.

V_S = _____ V
V_L = _____ V

15. Calculate the quality factor, Q, based on these measurements using equation (6) derived earlier.

$$Q = \frac{V_L}{V_S}$$

$$Q = \frac{(\quad)}{(\quad)}$$

MEASURED QUALITY FACTOR	Q = _____

How close is the measured Q to the theoretical Q of 2.242 calculated in the description? _____

_____

_____

8.5 OSCILLOSCOPE X_L AND X_C PHASE OBSERVATION

16. The current through L and C is the same. The voltage across L leads the current by 90° and the voltage across C lags by 90°. The voltages across L and C are thus out of phase by 180°. You will now observe these waveforms.

Connect the oscilloscope into the circuit as shown in Figure 3 to observe the voltages across L and C.

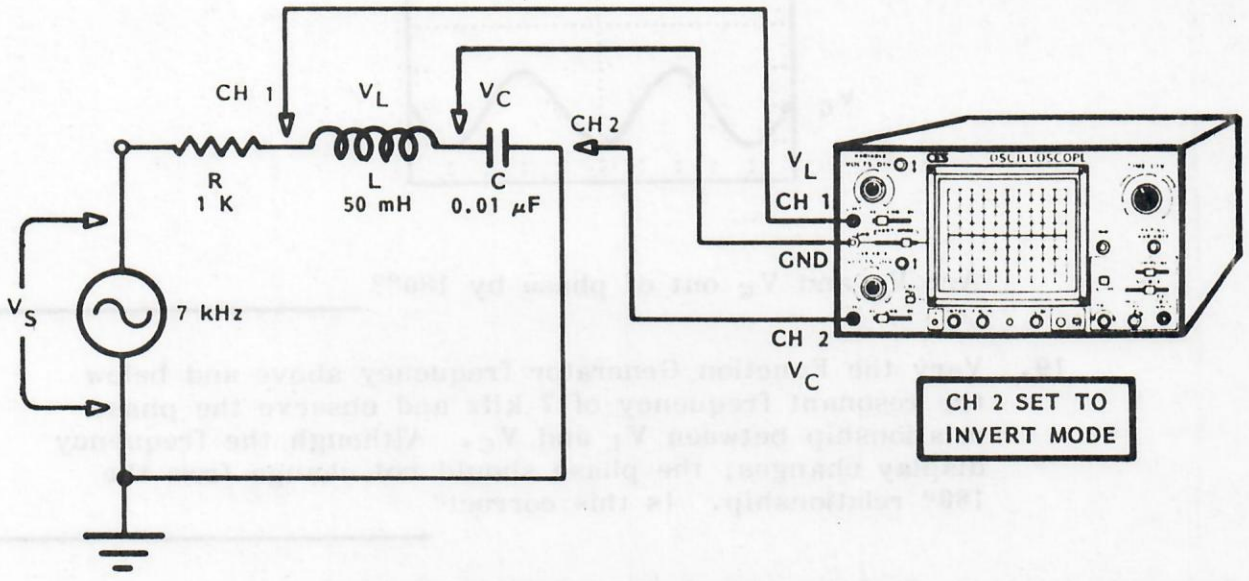


Figure 3 - Observation of L and C waveforms; EXPERIMENT.

17. Set the Function Generator output to 3 volts (using the ac meter.)

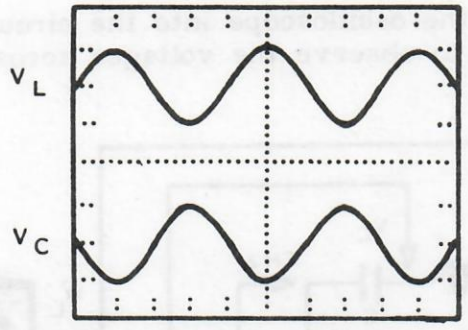
    Set the oscilloscope controls as follows:

    Set all VARIABLE controls to the CALIBRATE position.

CH 1 V/DIV	5 V
CH 2 V/DIV	5 V
VERTICAL MODE	ALT
CH 2 INVERT	INV (DEPRESSED)
SYNC SOURCE	CH 1
TIME/ DIV	10 μS

    The CH 2 INVERT switch must be depressed because the CH 2 input is reversed, that is, the CH 2 hot lead is connected to ground and the scope ground lead is connected to the junction of L and C.

18. Adjust the oscilloscope so that the waveforms are displayed as shown on the next page. V_L and V_C should be 180° out of phase as shown.



Are V_L and V_C out of phase by 180°? _____

19. Vary the Function Generator frequency above and below the resonant frequency of 7 kHz and observe the phase relationship between V_L and V_C. Although the frequency display changes, the phase should not change from the 180° relationship. Is this correct?

_____

8.6 V_{XL} AND V_{XC} AMPLITUDE OPERATION

20. You will now observe the amplitude of the voltages across L and C.

    At resonance, X_L and X_C are equal so that the voltage drops should be equal. Adjust the frequency until the amplitude of both voltages appear equal. This should occur at the resonant frequency.

21. A better way to see that both voltages are equal is to use the ADD mode on the oscilloscope if one is available. Because the voltages are 180° out of phase, they will cancel and the minimum amplitude will represent resonance.

    Set the VERTICAL MODE switch to ADD. Adjust the Function Generator frequency control for minimum voltage on the oscilloscope screen. (Ideally, the display should reduce to zero, but is prevented from doing so by the inductor resistance.)

    Read the resonant frequency setting of the Function Generator when the display is nulled.

RESONANCE AT NULL	f_r _____ kHz

22. Return the VERTICAL MODE from ADD to ALT. The inductor voltage, V_L, CH 1, should be at the top of the screen and V_C, CH 2, on the bottom.

Lower the generator frequency and observe that the inductor voltage amplitude becomes lower than the capacitor voltage. Is the circuit now inductive or capacitive? _____

_____

_____

23. Raise the frequency above resonance. Is the capacitive voltage greater or less than the inductive voltage? _____

Why? _____

_____

Is the circuit capacitive or inductive? _____

_____

8.7 VOLTAGE V_S AND CURRENT PHASES (OPTIONAL)

24. The applied voltage, V_S, and the total current, I_T, are in phase at resonance and I_T will lead or lag as the frequency varies.

Connect the oscilloscope to the circuit as shown in Figure 4 to observe both V_S and I_T.

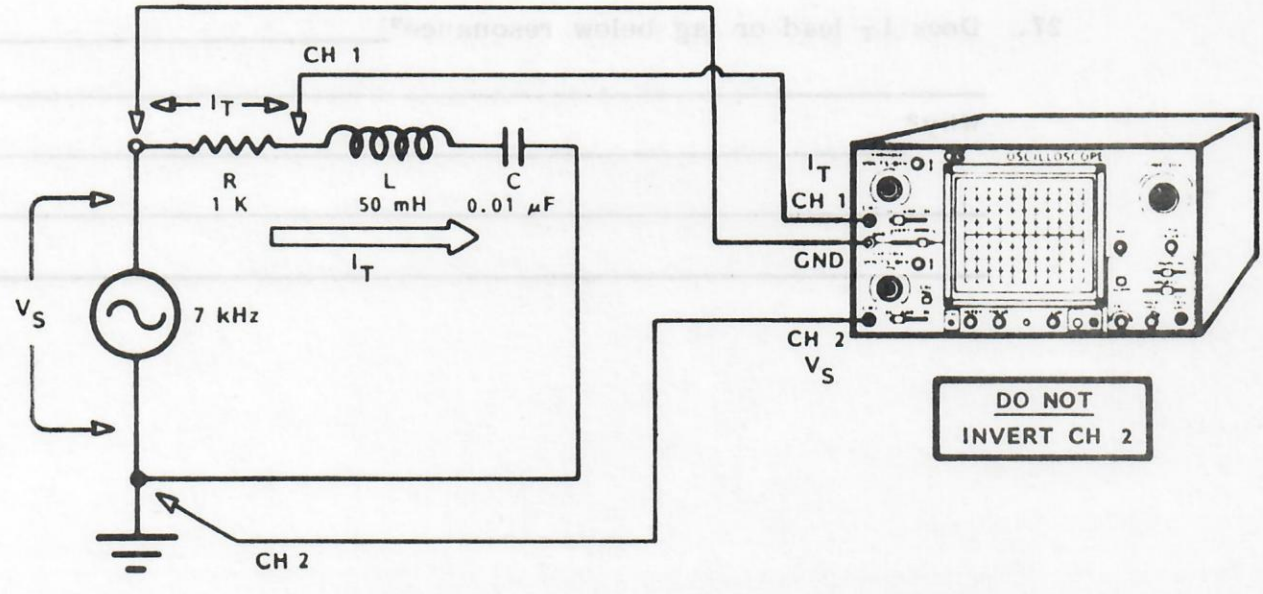
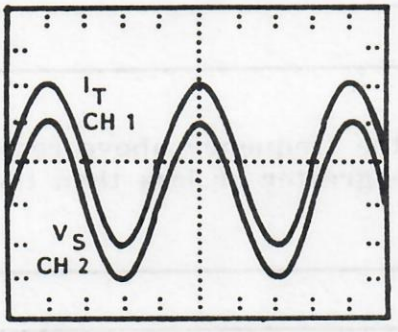


Figure 4 - Observation of V_S and I_T phase relationships; EXPERIMENT.

25. Adjust the display as shown below and set the frequency control at resonance. This will result in I_T (CH 1) and V_S (CH 2) waveforms in phase.



26. Vary the frequency above and below resonance and observe the I_T phase shift (top waveform) with respect to V_S. Does I_T lead or lag V_S above resonance?

_____

_____

Why? _____

_____

_____

27. Does I_T lead or lag below resonance? _____

_____

Why? _____

_____

_____

CONCLUSIONS

We have learned from this experiment that:

A series RLC circuit is resonant when X_C equals X_L.

The current in a series RLC circuit is maximum at resonance.

The reactive voltage drops in a series RLC circuit are maximum at resonance.

V_L and V_C are 180° out of phase and cancel each other.

The circuit impedance, at resonance, equals the series resistance.

The reactive voltage drops may be "magnified" near resonance, that is, they may be greater than the input voltage.

The amount of voltage magnification is a function of Q where:

$$V_L = Q\ V_S$$

When the frequency applied to a series RLC circuit is below resonance, the circuit current drops and V_L drops because X_L drops ($X_L = 2\pi fL$) and X_C has increased.

When the frequency applied to a series RLC circuit is above resonance, the circuit current drops and V_C drops because X_C drops ($X_C = 1/2\pi fc$) and X_L has increased.

The Q of an RLC resonant circuit can be calculated from the following measurements.

$$Q = \frac{V_L}{V_S} \qquad Q = \frac{X_L}{R} \qquad \text{where } X_L = \frac{V_L}{I_S}$$

ASSIGNMENT

Answer the following multiple choice questions.

1. In a series RLC circuit, at resonance, the impedance is equal to:

   a. X_C
   b. X_L
   c. R
   d. $X_L - X_C$ or $X_C - X_L$

2. In a series RLC circuit, at resonance:

   a. capacitive reactance is equal to the inductive reactance.
   b. the voltage drop across LC is equal to zero.
   c. the impedance is equal to $\sqrt{R^2 + (X_L - X_C)^2}$
   d. all of the above.

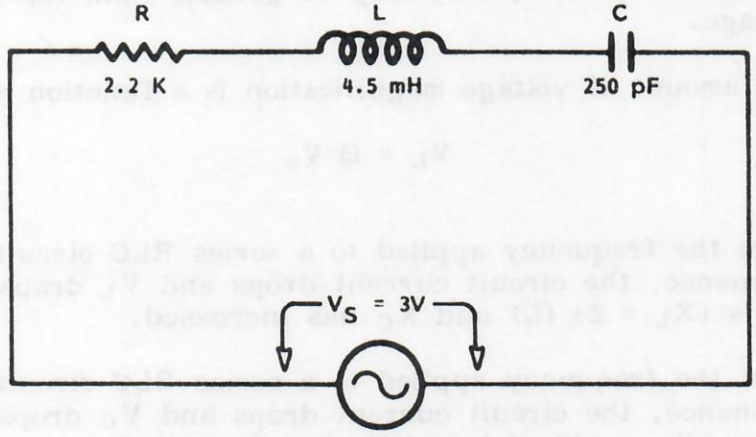


Figure 5 refers to questions 3 to 10.

3. The resonant frequency of the RLC circuit in Figure 5 is closest to:

   a. 150 Hz.
   b. 37.6 kHz.
   c. 150 kHz.
   d. 150 mHz.

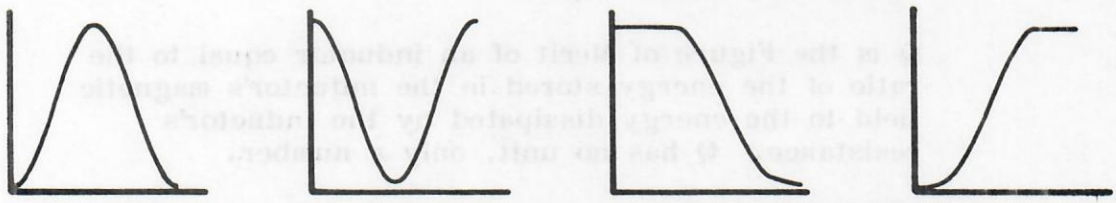
4. At resonance, the impedance of the inductor, L, in Figure 5, is closest to:

   a. 42,390 Ω.
   b. 23,500 Ω.
   c. 13,500 Ω.
   d. 23,500 μH.

5. The capacitive reactance of C in Figure 5 is closest to:

   a. the value of R, 2.2 K.
   b. 23,500 Ω.
   c. 250 pf.
   d. 42,390 Ω.

6. The plot of impedance versus frequency for the circuit of Figure 5 is:



a. b. c. d.

7. In the circuit of Figure 5, at resonance, the voltage drop across L is:

   a. equal to $(I_S)(X_C)$.
   b. leading I_L by 90°.
   c. 90° out of phase with V_C.
   d. all of the above.

8. In the circuit of Figure 5, at resonance, the current flow in the series circuit will be:

   a. close to zero.
   b. equal to V_S/X_L.
   c. equal to V_S/R.
   d. equal to V_S/X_C.

9. Given a voltage drop of 58 volts across L, in Figure 5, the circuit Q is closest to:

   a. 19.
   b. 29.
   c. 58.
   d. insufficient data.

10. When f, in Figure 5, is dropped below resonance:

   a. X_C increases.
   b. V_C increases.
   c. X_L increases.
   d. both a and b.

KEY TERMS

1. CAPACITIVE REACTANCE (X_C)

   The opposition to the flow of ac through a capacitor. It is measured in ohms, indicated as X_C and calculated from

$$X_C = \frac{1}{2\pi fC}$$

2. FIGURE OF MERIT (Q)

   Q is the Figure of Merit of an inductor equal to the ratio of the energy stored in the inductor's magnetic field to the energy dissipated by the inductor's resistance. Q has no unit, only a number.

3. IMPEDANCE (Z)

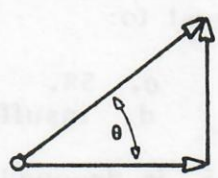
   The resulting total opposition to the flow of ac when resistance, capacitive reactance and inductive reactance are in the circuit. Impedance is defined as Z and is measured in ohms.

4. INDUCTIVE REACTANCE (X_L)

   The opposition to the flow of ac through an inductor. It is measured in ohms, indicated as X_L and calculated from $X_L = 2\pi fL$.

5. PHASE ANGLE (θ)

   The number of degrees by which the current leads or lags the applied voltage. The phase angle is defined by the Greek letter θ. It is shown on a phasor diagram as



6. PHASOR

   A phasor, also known as a vector, is used to indicate magnitude and direction as compared to a reference quantity. This is illustrated in 5 above.

7. Q

See 2 above, Figure of Merit.

8. REACTANCE (X)

Opposition to the flow of ac by an inductor or capacitor. Reactance is measured in ohms and indicated as X (X_C or X_L).

9. RESONANCE

A condition in a circuit that contains both L and C where X_C equals X_L. This will occur at one frequency only, called the Resonant Frequency. The resonant frequency is determined from

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

10. VOLTAGE MAGNIFICATION

An effect that can occur in a series resonant circuit where the voltage drops across the reactive components, at resonance, are equal but greater then the source voltage. The higher the circuit Q, the greater the voltage magnification.

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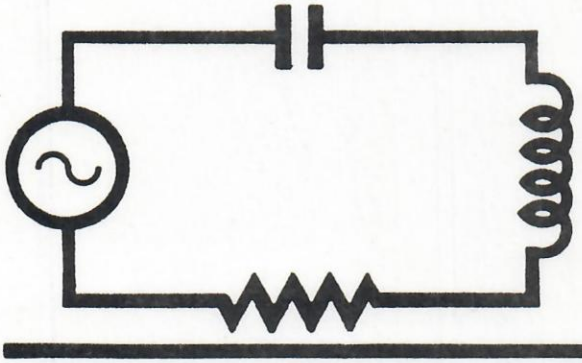

G5

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PART G5

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Safety Notes

1. Be sure to review safety procedures in the lab with your instructor.

2. Do not use any external power supply with the Ed-Lab 651 Electronics Trainer.

3. Safety is using good common sense, being careful and never horsing around. Electrical shock can result in death. Improper use of equipment can accidentally result in severe injury.

4. A complete lesson on safety is located at the beginning of Part G1. Review this lesson.

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AC CIRCUITS
PART G5

Parallel Resonance 9

OBJECTIVES

When you finish this experiment you will be able to:

1. Calculate the resonant frequency of a parallel RLC circuit.
2. Draw the phasor diagram for a parallel resonant RLC circuit.
3. Measure and plot the band pass and band stop response curves for a parallel resonant RLC cirucit.
4. Measure the Q of a parallel resonant RLC circuit.
5. Measure the bandwidth of a parallel resonant RLC circuit.
6. Test the radiation of high frequency signals through air.
7. Change the tuning range of an RLC circuit.
8. Display the frequency response curve of an RLC resonant circuit on an oscilloscope screen.
9. Increase the frequency range of the Function Generator up to 200 kHz using the f_{VCO} jack.

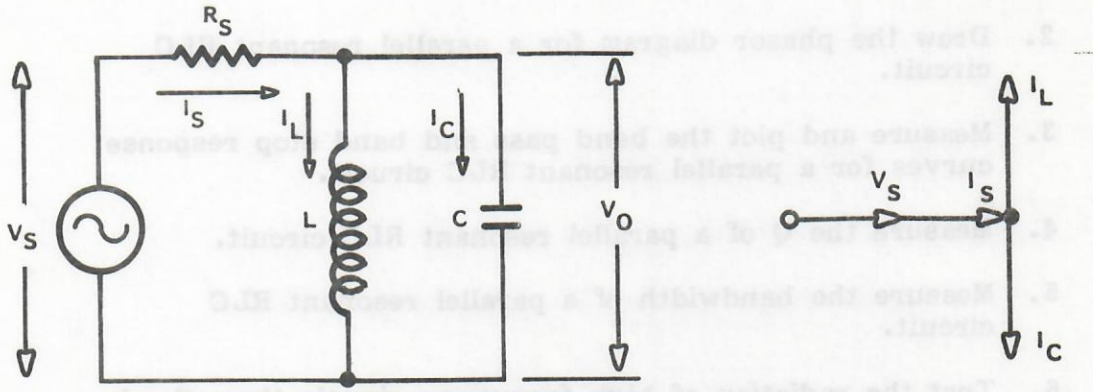
DESCRIPTION

Series and parallel RLC circuits were discussed in earlier experiments. Also discussed in an earlier experiment was the RLC series resonant circuit. In this experiment, you will learn about the RLC parallel resonant circuit and some of its applications.

Recall that resonance was described earlier as the frequency at which X_C equals X_L in a series RLC circuit. The same definition holds true for a parallel RLC circuit. The equation to determine the resonant frequency of a parallel tuned circuit is the same as for a series tuned circuit and is:

PARALLEL RESONANCE	$f_r = \frac{1}{2\pi\sqrt{LC}}$

A parallel resonant circuit is shown in Figure 1(a). The same voltage appears across L and C. At resonance, when X_L and X_C are equal, the branch currents must also be equal. They are out of phase by 180° because the inductor current lags the voltage by 90° and the capacitor current leads the voltage by 90°. Therefore, the sum of the two currents is zero.

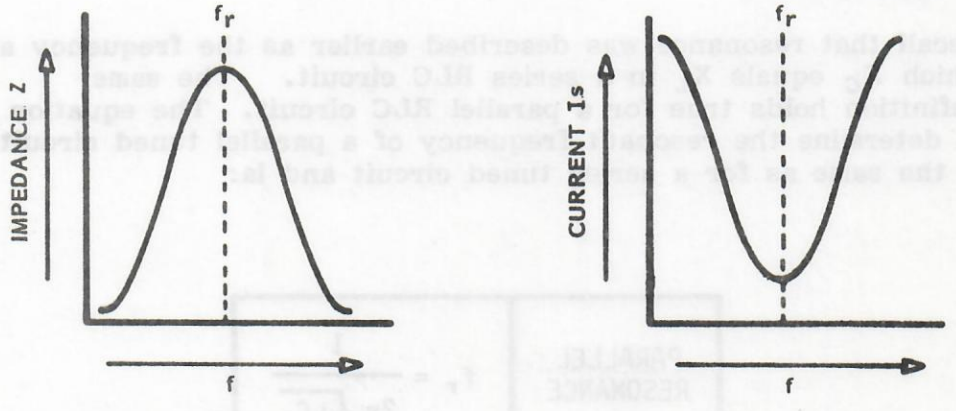


(a) PARALLEL RLC CIRCUIT (b) PARALLEL RLC PHASOR

Figure 1 - Parallel resonant circuit and phasor.

Because I_L and I_C cancel, there is no series current, I_S, and therefore no voltage across R_S and thus a maximum voltage drop across the output, V_O.

When the LC "tank" circuit input frequency is adjusted off resonance, above and below, the reactances do not cancel and current is drained from the source. The further the circuit is tuned from resonance, the more current is drained from the source and the lower the output voltage drops. Stated another way, the further the circuit is tuned from resonance, the lower its impedance. The resonance curves for a parallel LC "tank" circuit are shown in Figure 2.



(a) Z vs FREQUENCY (b) I vs FREQUENCY

Figure 2 - Resonance curves for parallel LC circuits.

Note that while the curve shape (called a BELL curve) is the same as that for the series resonant circuit, the parallel impedance is maximum and the current is minimum at resonance. This is the opposite of the series circuit where the current was maximum and the impedance minimum at resonance.

CIRCUIT Q

The parallel LC resonant circuit, at resonance, has infinite impedance and draws no LINE current from the source. The capacitor and the inductor exchange current (called the TANK current), which is at a maximum. Theoretically, once the source voltage charges the tank circuit, L and C will alternately exchange energy without requiring any further charge. In practice, you know that the inductor has resistance, R_L, which dissipates energy that cannot be returned to the circuit. The lost energy must be made up by the source. The higher the inductor resistance, R_L, the greater the losses and more line current is required to recharge the tank. The resistance of the inductor in the parallel LC circuit and the Line and Tank current paths are shown in Figure 3.

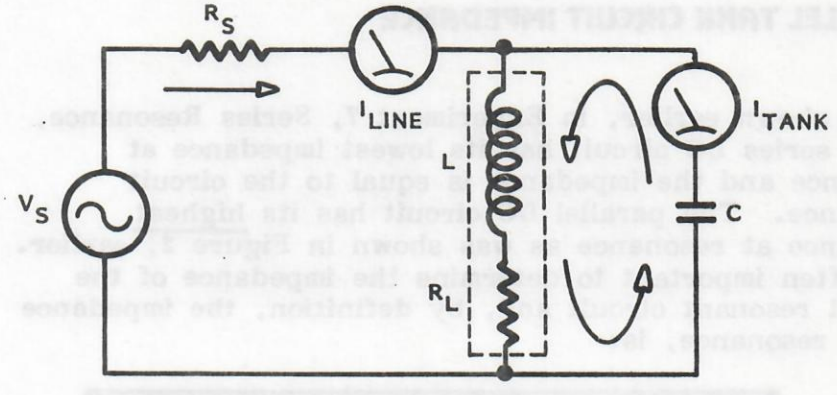


Figure 3 - Parallel LC circuit current paths and resistance.

The greater the value of R_L in Figure 3, the greater is the energy dissipated in heat that does not return to the circuit. This lost energy is made up by the source thus increasing the line current, I_{LINE} . The greater the value of R_L, the lower the tank circuit Q. The quality factor, Q, was defined earlier as the ratio of inductive power to resistive power, or:

$$Q = \frac{P_{XL}}{P_R} \qquad (1)$$

This value of Q is the same as that for the series LC circuit and because the current in L and R are equal, was also shown to be equal to:

PARALLEL CIRCUIT; COIL Q	$Q = \frac{X_L}{R_L}$

(2)

The Q may also be shown to be related to the ratio between the line current, I_{LINE}, and the current circulating between the inductor and capacitor, called the TANK CURRENT, I_{TANK}. Thus:

$$Q = \frac{I_{TANK}}{I_{LINE}} \qquad (3)$$

This is not a practical equation to use because it is very difficult to actually measure the tank current.

PARALLEL TANK CIRCUIT IMPEDANCE

It was shown earlier, in Experiment 7, Series Resonance, that a series LC circuit has its lowest impedance at resonance and the impedance is equal to the circuit resistance. The parallel LC circuit has its highest impedance at resonance as was shown in Figure 2, earlier. It is often important to determine the impedance of the parallel resonant circuit and, by definition, the impedance (Z) at resonance, is:

IMPEDANCE AT RESONANCE	$Z = \frac{V_L}{I_{LINE}}$ or $\frac{V_C}{I_{LINE}}$

(4)

If the impedance of a resonant circuit is a function of the line current, I_{LINE}, and it was noted that I_{LINE} is a function of Q, then Z must be related to Q and, by extension, to the inductor resistance, R_L.

To calculate the theoretical impedance of a parallel tank circuit, any one of the following equations may be used as well as equation (4) above.

$$Z = X_L\ Q \tag{5}$$

$$Z = Q^2\ R_L \tag{6}$$

$$Z = \frac{X_L^2}{R_L} \tag{7}$$

$$Z = \frac{L}{C\ R_L} \tag{8}$$

Given a parallel resonant tank circuit with an X_L of 700 ohms and a resistance of 4 ohms, the circuit Q will be:

$$Q = \frac{X_L}{R}$$

$$Q = \frac{700}{4}$$

$$Q = 175$$

The impedance of this parallel resonant circuit can be determined using any of the above equations for which the data are available. Using equation (5), we have:

$$Z = X_L\ Q$$

$$= (700)(175)$$

$$Z = 122.5\ K$$

Using the other applicable equations, we have:

$$Z = Q^2 \, R_L \qquad (6)$$

$$= (175^2)(4)$$

$$\boxed{Z = 122.5 \text{ K}}$$

or

$$Z = \frac{X_L{}^2}{R_L} \qquad (7)$$

$$= \frac{700^2}{4}$$

$$\boxed{Z = 122.5 \text{ K}}$$

CIRCUIT Q FOR PARALLEL CIRCUIT RESISTANCE

When a parallel resonant LC tank is connected into a circuit, the external circuit resistance is immediately in parallel with that tank circuit. The result is shown in Figure 4 where the parallel resistance, R_P, can represent the internal resistance of the source or the internal resistance of a load connected across the tank circuit, or both.

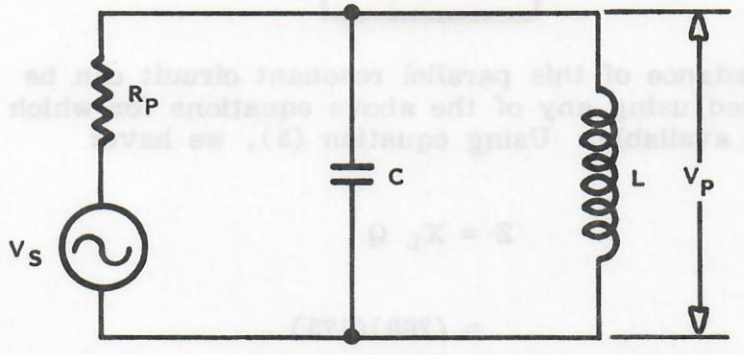


Figure 4 - Circuit resistance in parallel with the tank circuit.

The presence of R_P lowers the Q of the circuit, not the Q of the coil, because R_P dissipates energy in the form of heat that cannot be returned to the circuit. The equation for the Q of the circuit, as affected by the parallel resistance, R_P, is developed below. The definition of Q is:

$$Q = \frac{P_{XL}}{P_R} \tag{1}$$

Expanding this for a parallel circuit, we have:

$$Q = \frac{\frac{V_P^2}{X_L}}{\frac{V_P^2}{R_P}} \tag{9}$$

Because, in a parallel circuit, the voltage, V_P, across the inductor and the parallel resistance is the same, they cancel and we have:

$$Q = \frac{\frac{1}{X_L}}{\frac{1}{R_P}} \tag{10}$$

This equation simplifies to:

PARALLEL RESISTOR, CIRCUIT Q	$Q = \frac{R_P}{X_L}$

(11)

From the above, it may be seen that the LOWER the value of R_P, the parallel resistance, the lower the circuit Q. For the coil, the lower the series resistance, the greater the Q. In some applications, resistances are placed in parallel with the tank circuits to lower the Q and thus increase the bandwidth to a desired value. One typical example is in FM radios.

BANDWIDTH

The output response of a typical parallel resonant circuit, as the frequency varies, is shown in Figure 5 where f is plotted against impedance (Z) and voltage (E) which are both maximum at resonance.

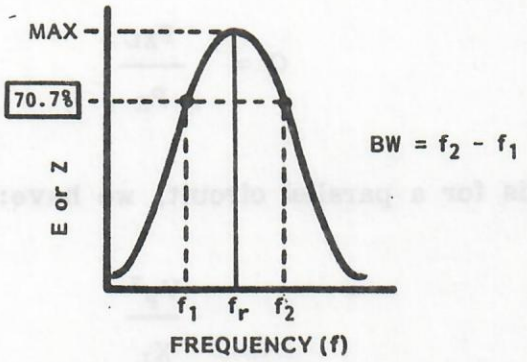


Figure 5 - Bandwidth determination.

The half power points are $1/\sqrt{2}$ or 70.7% of maximum voltage or impedance as marked-off in Figure 5. The bandwidth is that range of frequencies between the half power points, f_1 and f_2, thus:

$$BW = f_2 - f_1$$

Because the bandwidth is a function of Q, it can be shown that:

$$BW = \frac{f_r}{Q}$$

PARALLEL TANK APPLICATIONS

Two applications of the parallel resonant tank circuit are shown in Figure 6(a) and (b).

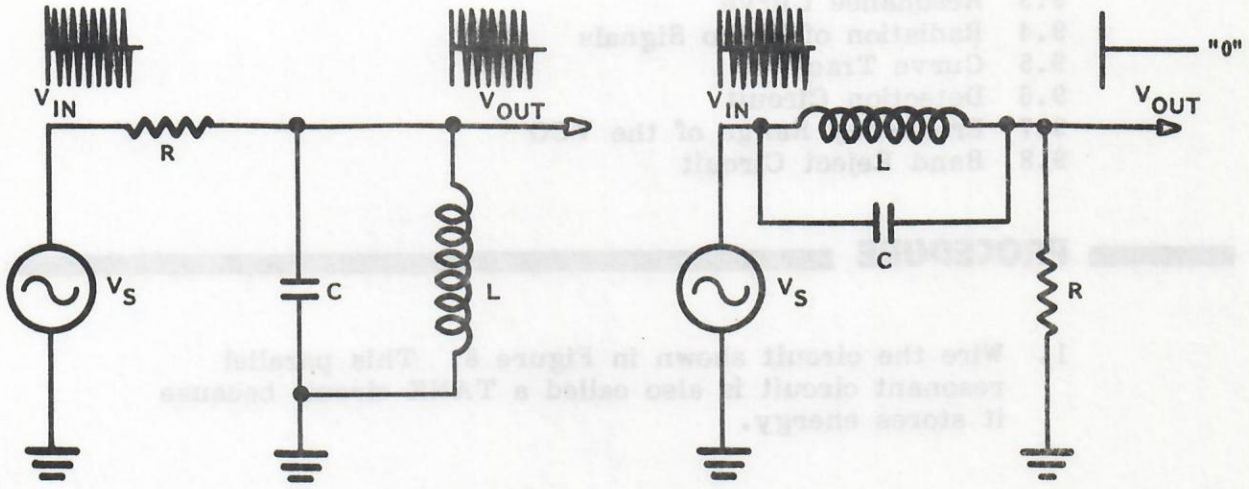


Figure 6 - Parallel resonant band pass and stop circuits.

In Figure 6(a), at resonance, the tank circuit is at maximum impedance (theoretically, at infinite Z), no current flows through R, and the output voltage is at maximum. As the input frequency deviates from f_r, current flows and V_{OUT} decreases. The circuit provides more than half power output for all frequencies in the f_1 - f_2 "band pass" range. The band pass response curve is that shown earlier in Figure 2(a) and Figure 5.

For the circuit in Figure 6(b), at resonance the tank also has infinite Z (theoretically) so this circuit serves a band stop function. The band stop response curve is shown in Figure 7.

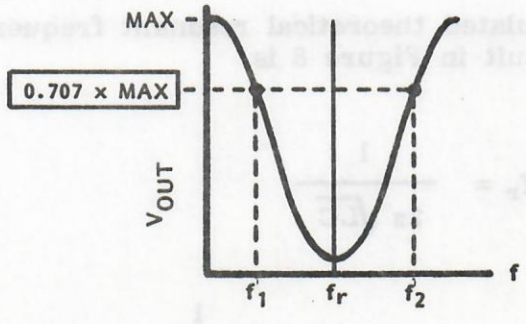


Figure 7 - Band stop response curve and half power points.

PARTS OF EXPERIMENT

This experiment consists of 8 parts which include:

9.1 Parallel Resonant Circuit
9.2 Bandwidth
9.3 Resonance Curve
9.4 Radiation of Radio Signals
9.5 Curve Tracer
9.6 Detection Circuit
9.7 Frequency Range of the VCO
9.8 Band Reject Circuit

PROCEDURE

1. Wire the circuit shown in Figure 8. This parallel resonant circuit is also called a TANK circuit because it stores energy.

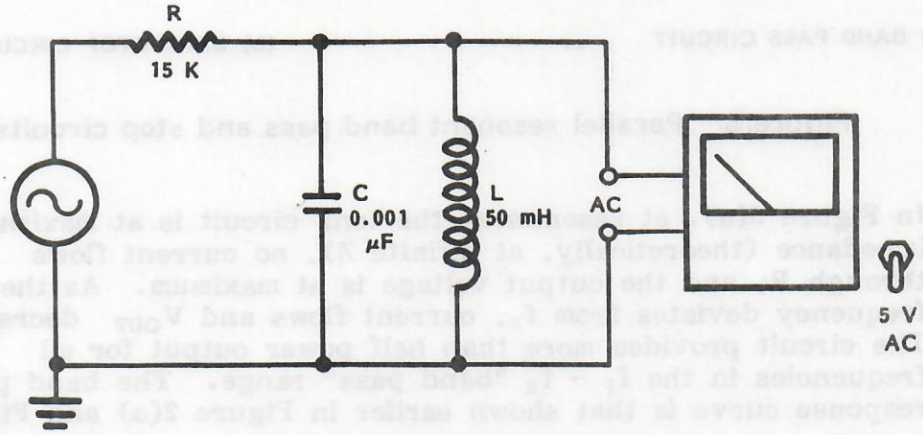


Figure 8 - Parallel resonant tank circuit EXPERIMENT.

9.1 PARALLEL RESONANT CIRCUIT

2. The calculated theoretical resonant frequency for the tank circuit in Figure 8 is:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{(6.28)\sqrt{(50 \times 10^{-3})(0.001 \times 10^{-6})}}$$

$$= \frac{1}{6.28 \times 10^{-6}\sqrt{50}} = \frac{10^6}{(6.28)(7.07)}$$

f_r = 22,500 Hz

3. Set the Function Generator Range control to the 10 K - 100 K position and set the SINE AMPL. control to maximum output (CW).

4. Vary the generator frequency until the ac voltmeter indicates a peak. Vary the Frequency knob back and forth across resonance carefully until you have the best adjustment for peak. Enter the resonant frequency below.

f_r = _____ Hz

This should be very close to the calculated value (from step 2) of 22,500 Hz.

9.2 BANDWIDTH

5. The bandwidth, BW, is determined in the same manner as for the series resonant circuit. The f_1 and f_2 points are found at 0.707 times the peak voltage.

With the Function Generator set at resonance, adjust the Sine Ampl. control for an output of 3 volts on the meter.

6. Now vary the frequency control to the half power point voltage of 2.12 volts (0.707 x 3 volts.) Read the low (f_1) and high (f_2) frequencies and record them below.

LOW HALF POWER POINT	f_1 = _____ kHz

HIGH HALF POWER POINT	f_2 = _____ kHz

7. Calculate the bandwidth (BW) based on the f_1 and f_2 measurements.

$$BW = f_2 - f_1$$

$$= (\quad) - (\quad)$$

BW = _____ kHz

8. Calculate the Quality Factor, Q, given by:

$$Q = \frac{f_r}{BW}$$ ← (From Step 4) ← (From Step 7)

$$Q = \frac{(\quad)}{(\quad)}$$

Q = _____

Is the Q that of the circuit or the Q of the coil ? _____

9. The theoretical Q of the parallel resonant RLC circuit is given by:

$$Q = \frac{R_P}{X_L} = \frac{R_P}{2\pi fL}$$

In this circuit, R_P is equal to 15 K plus the 100 ohm generator resistance which is shown to be effectively in parallel with the tank circuit in Figure 9.

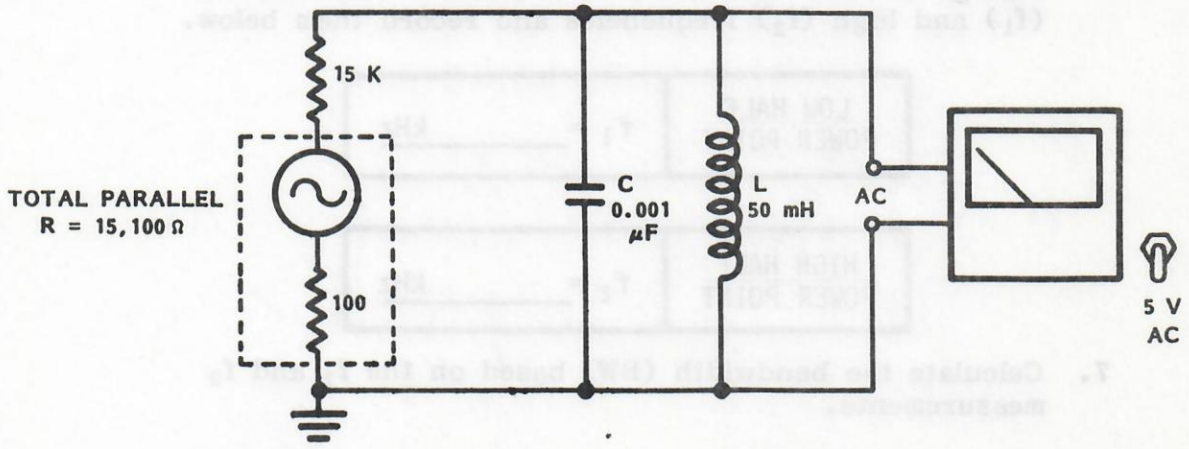


Figure 9 - Equivalent circuit of Figure 8.

Based on the equivalent circuit of Figure 9, the theoretical Q, using f determined in step 4, is:

$$Q = \frac{R_{PARALLEL}}{2\pi fL}$$

$$Q = \frac{15,100}{(6.28)(\quad)(50 \times 10^{-3})}$$

$$Q = \frac{15,100}{(\quad)}$$

THEORETICAL CIRCUIT Q	Q = _____

How does the theoretical Q above compare to the measured Q from step 8?

_____

_____

9.3 RESONANCE CURVE (OPTIONAL)

10. The major points of interest for a resonant tank circuit are the resonant frequency and the high and low half power points. In this step, however, you will plot the entire response curve in order to locate and mark off the points of interest.

Adjust the frequency control to produce the highest meter reading. This is the resonant frequency to be recorded below. It should be the same as before.

f_r = _____ kHz

Adjust the SINE AMPL. control for a reading of 3 volts at resonance.

11. Adjust the Function Generator to each of the frequencies listed in Table 1 and enter the voltage readings in the column marked PASS.

FREQUENCY IN kHz	VOLTAGE READINGS	
	PASS	STOP
1		
5		
10		
15		
20		
25		
30		
35		
40		
45		
50		

TABLE 1 - Parallel resonant voltage readings.

12. Plot the resonance curve on the graph in Figure 10 using the data from Table 1, the resonant frequency from step 10, and the half power point frequencies from step 6.

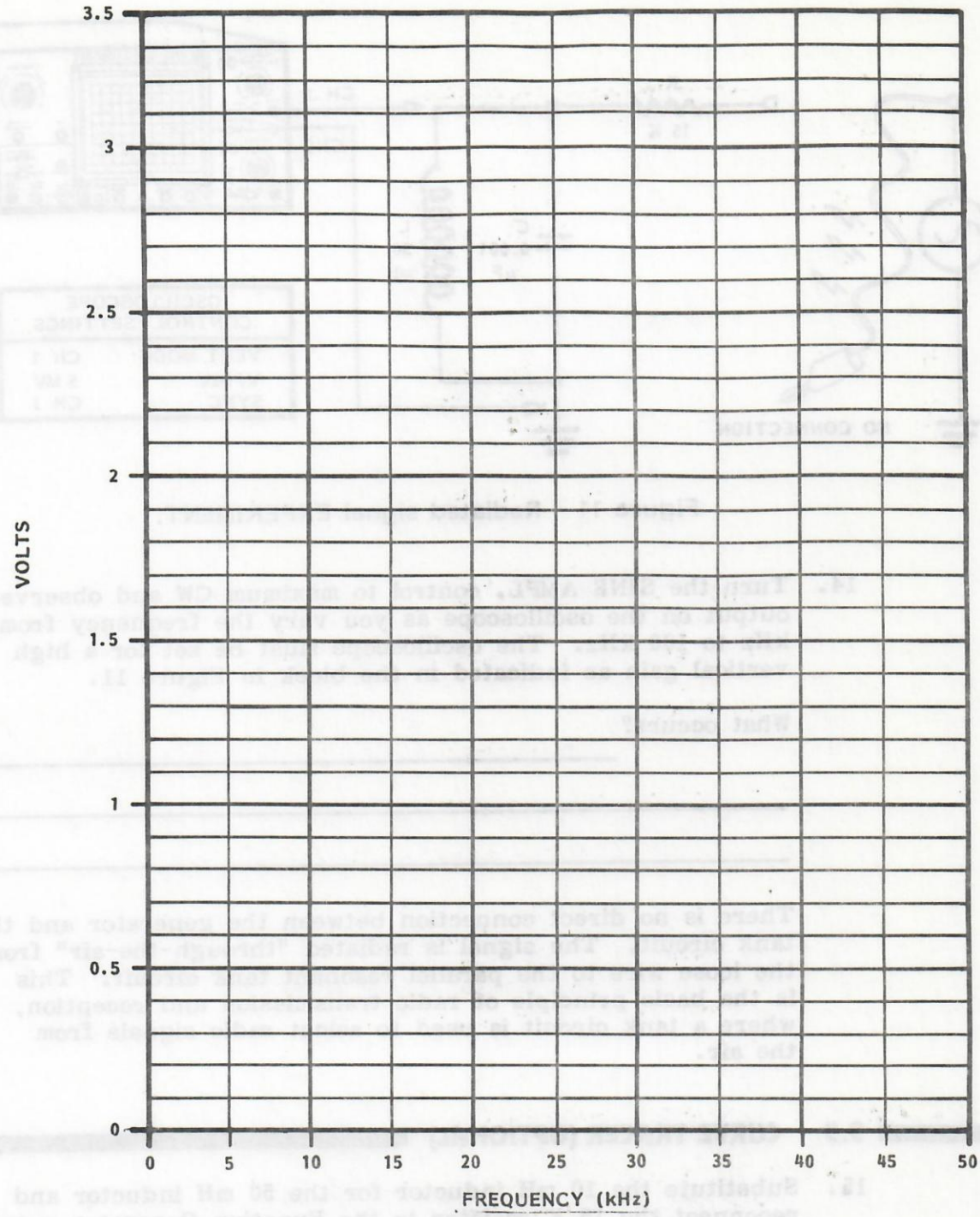


Figure 10 - Graph for plotting response curve.

9.4 RADIATION OF RADIO SIGNALS

13. Wire the oscilloscope to the same circuit, as in Figure 11. You may leave the meter connected. Leave the end of the lead in the Function Generator output jack but remove the end from the connection to the 15 K resistor. Let this wire hang loose. This results in the circuit arrangement shown in Figure 11 where there is no direct connection between the generator signal and, the tuned circuit.

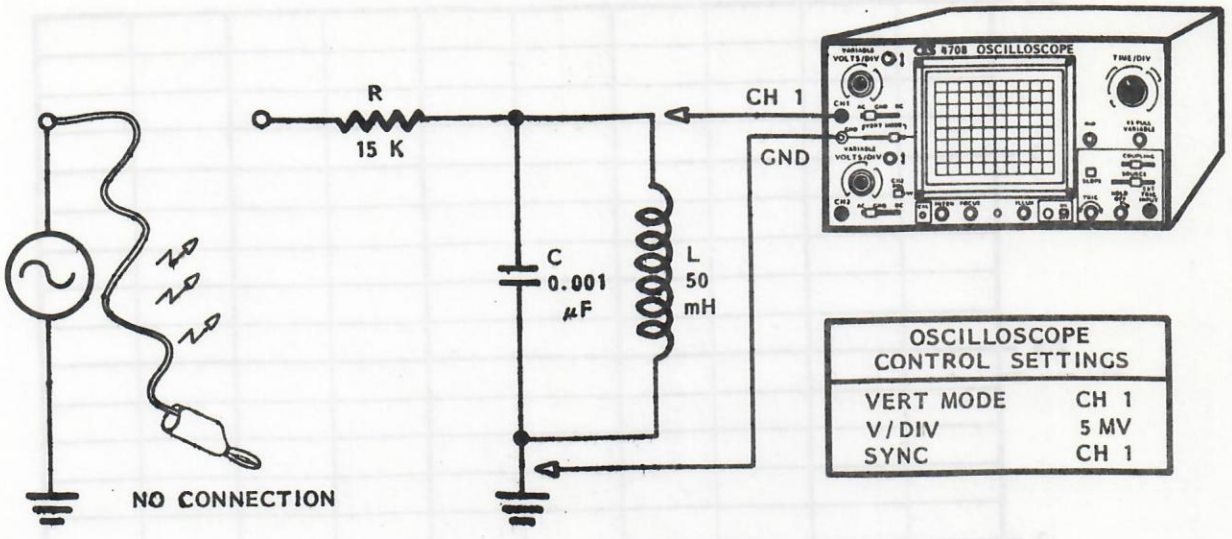


Figure 11 - Radiated signal EXPERIMENT.

14. Turn the SINE AMPL. control to maximum CW and observe the output on the oscilloscope as you vary the frequency from 10 kHz to 100 kHz. The oscilloscope must be set for a high vertical gain as indicated in the block in Figure 11.

What occurs?

_____

_____

_____

There is no direct connection between the generator and the tank circuit. The signal is radiated "through-the-air" from the loose wire to the parallel resonant tank circuit. This is the basic principle of radio transmission and reception, where a tank circuit is used to select radio signals from the air.

9.5 CURVE TRACER (OPTIONAL)

15. Substitute the 10 mH inductor for the 50 mH inductor and reconnect the 15 K resistor to the Function Generator output as shown in Figure 12.

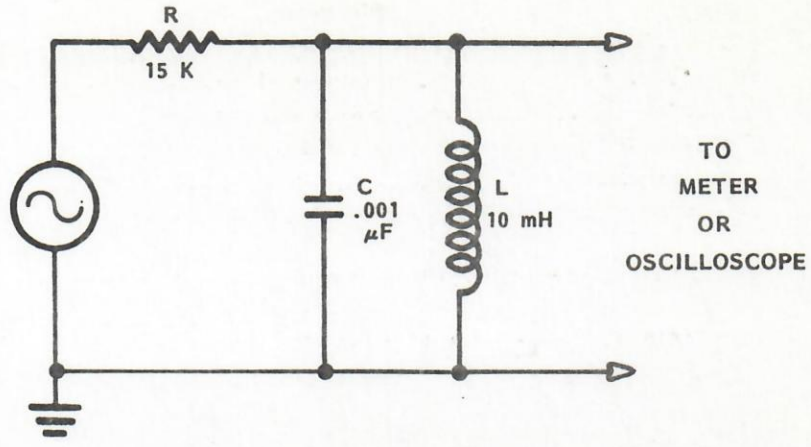


Figure 12 – Substitution of the 10 mH inductor; EXPERIMENT.

Calculate the new resonant frequency from:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

where $L = 10\ mH = 10 \times 10^{-3}\ H$
$C = 0.001\ \mu F = 0.001 \times 10^{-6}\ F$

$$f_r = \frac{1}{6.28\sqrt{(\qquad)(\qquad)}}$$

THEORETICAL RESONANT FREQUENCY	f_r = _____ kHz

16. Vary the Function Generator frequency until the new resonant frequency is obtained. What is the new measured frequency?

MEASURED FREQUENCY FOR 10 mH	f_r = _____ kHz

Comment on these results. Was the resonant frequency higher or lower than before and why?

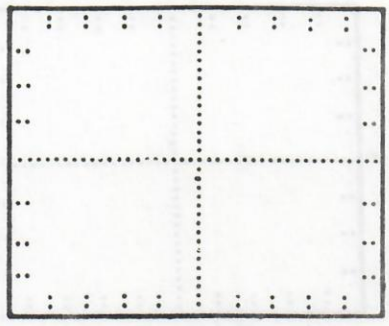
_____

_____

_____

21. Rapidly rotate the 10 K pot knob in both directions and observe the display on the screen.

Sketch the display shown, below.



9.6 DETECTION CIRCUIT (OPTIONAL)

22. The output display in step 17 showed the full ac signal variation. It is possible to view only the peak sine wave output to produce the actual resonance curve that we have plotted in this experiment by using the DIODE DETECTOR circuit described in earlier experiments. Add the circuit shown in the dotted enclosure in Figure 14.

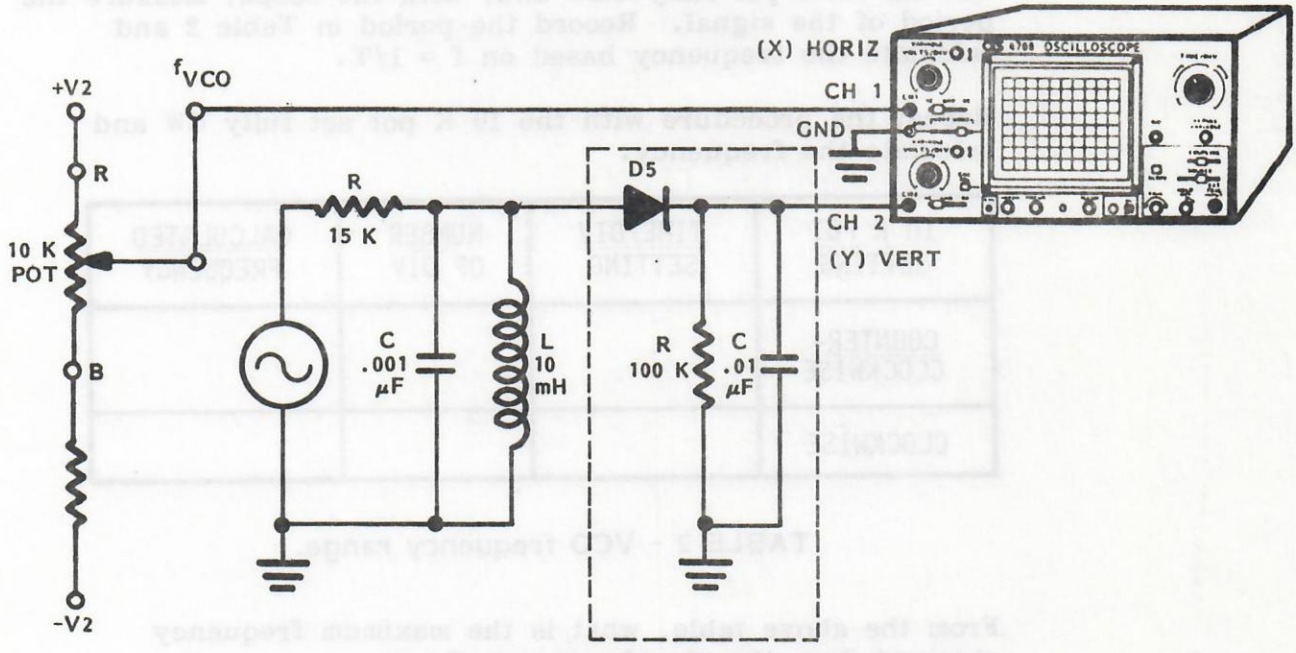
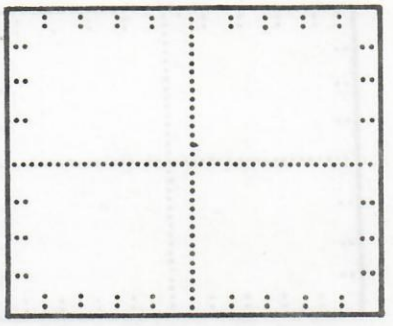


Figure 14 - Detector/Filter circuit in dotted enclosure; EXPERIMENT.

23. Rapidly vary the 10 K pot knob in both directions as before, and observe the display.

Sketch the display shown, below.



9.7 FREQUENCY RANGE OF THE VCO

24. You will now measure the maximum frequency range of the Function Generator as controlled by the VCO voltage. Change the oscilloscope settings for normal waveform observation on CH 1 and connect the CH 1 input directly to the Function Generator output.

25. Set the Function Generator frequency to 100 kHz.

Set the 10 K pot fully CCW and, with the scope, measure the period of the signal. Record the period in Table 2 and calculate the frequency based on f = 1/T.

Repeat the procedure with the 10 K pot set fully CW and calculate the frequency.

10 K POT SETTING	TIME/DIV SETTING	NUMBER OF DIV	CALCULATED FREQUENCY
COUNTER-CLOCKWISE			
CLOCKWISE			

TABLE 2 - VCO frequency range.

From the above table, what is the maximum frequency obtained from the signal generator?

_____

_____

_____

9.8 BAND REJECT CIRCUIT (OPTIONAL)

26. Remove all existing wiring and wire the circuit shown in Figure 15.

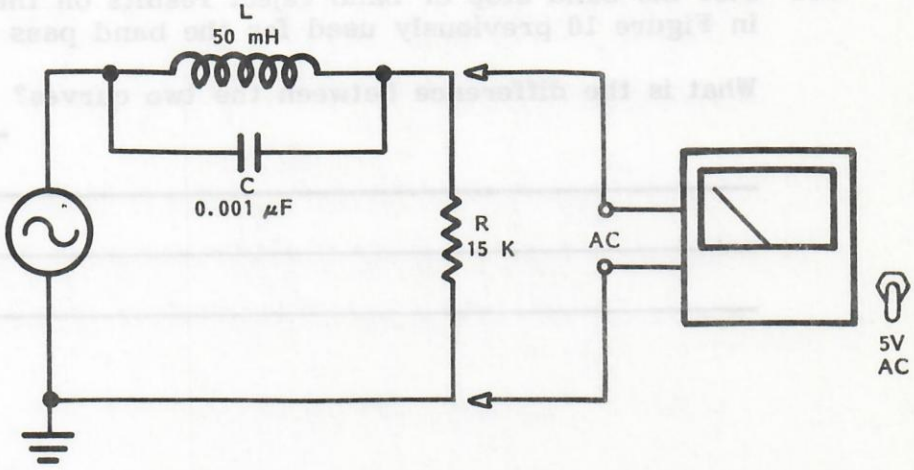


Figure 15 - Parallel resonant Band Stop filter EXPERIMENT.

27. Set the Function Generator Range knob to the 10 kHz - 100 kHz setting.

Vary the input frequency until a minimum voltage reading is obtained. Record this resonant frequency and the voltage below.

BAND STOP RESONANT FREQUENCY	f_r = _____ kHz

RESONANT VOLTAGE	V_{fr} = _____ V

28. You will now plot the band stop resonance curve.

Set the Function Generator frequency to 1 kHz (a frequency which is very much off-resonance).

Vary the Function Generator amplitude knob to adjust the output voltage to 3 volts.

Record this output voltage (3 volts) in the BAND STOP column of Table 1 in step 11, corresponding to the 1 kHz row.

29. Now vary the frequency to the values listed in Table 1 and enter each of the voltage readings in the STOP column.

30. Plot the band stop or band-reject results on the graph in Figure 10 previously used for the band pass curve.

What is the difference between the two curves?

CONCLUSIONS

The resonant frequency of a parallel resonant LC tank circuit is calculated using:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

This is the same equation used for series resonant circuits.

In the parallel resonant circuit, at resonance, X_L equals X_C just as in the series resonant circuit.

At resonance, a parallel resonant circuit has maximum impedance.

At resonance, the voltage source delivers minimum current to the tank circuit.

The coil Q, for the series resistance that is part of the inductor, R_S, is determined from:

$$Q = \frac{X_L}{R_L} \qquad \text{(COIL Q)}$$

just as for the series RLC circuit.

For the parallel resistance in the parallel RLC circuit, the Q is determined from:

$$Q = \frac{R_P}{X_L} \qquad \text{(CIRCUIT Q)}$$

The parallel resistance has a major effect on the Q of the tank circuit.

R_P increases the line current but does not increase the tank current. Because Q is also equal to:

$$Q = \frac{I_{TANK}}{I_{LINE}}$$

increasing I_{LINE} without a corresponding increase in I_{TANK}, lowers Q.

The tank circuit impedance, at resonance, is equal to:

$$Z = \frac{V_L}{I_{LINE}} \qquad \text{and} \qquad Z = (X_L)(Q)$$

The bandwidth of a parallel resonant circuit is measured between the half power points which are located at 0.707 times the peak or resonant voltage.

The parallel resonant circuit can be wired in the band pass or band stop configurations.

The bandwidth of the parallel resonant circuit is found from:

$$BW = \frac{f_r}{Q} \qquad \text{and} \qquad BW = f_2 - f_1$$

Radio frequency signals (RF) will travel through air and can be "picked-up" by a resonant circuit tuned to that radio frequency.

The frequency range of a tuned circuit can be shifted by changing the value of L or C.

The response curve of the tuned circuit can be displayed on an oscilloscope screen using a CURVE TRACER circuit.

ASSIGNMENT

Answer the following multiple choice questions.

1. A resonant circuit consists of a parallel R, L and C components. The resistor is removed from the circuit but no other change is made. This causes:

   a. f_r to increase.
   b. f_r to decrease.
   c. Q to increase.
   d. Z to drop.

2. For a parallel resonant RLC circuit, at resonance, where in theory only, R_L is zero, the impedance is equal to:

   a. X_L.
   b. R_p.
   c. C.
   d. (R)(Q).

3. For a practical LC parallel resonant circuit, the impedance can be approximated from:

   a. $(Q)(X_L)$.
   b. (R)(Q).
   c. $R^2\sqrt{(X_L - XC)^2}$.
   d. any of the above.

4. For the parallel RLC circuit, at resonance, the impedance is _____ and the line current is _____.

   a. high; low
   b. high; high
   c. low; high
   d. low; low

5. In a parallel resonant circuit, Q can be determined from the ratio of _____ to _____.

   a. I_R; I_C
   b. I_{TANK} ; I_{LINE}
   c. I_C; I_R
   d. I_{LINE} ; I_{TANK}

6. To increase the bandwidth of a parallel resonant RLC circuit, it is necessary to:

   a. decrease the coil resistance.
   b. increase the value of the parallel resistor.
   c. remove the parallel resistor from the circuit.
   d. lower the value of the parallel resistor.

7. A 50 ohm X_L (with no dc resistance) and a 50 ohm X_C are placed in parallel across a 100 volts ac source that has a 25 ohm internal resistance. At resonance, the current flow will be:

   a. 2 A.
   b. 1 A.
   c. 0.8 A.
   d. 0 A.

8. In a parallel resonant circuit_____ is 180° out of phase with_____.

   a. E_L; I_L
   b. I_L; I_C
   c. I_L; E_L
   d. E_L; E_C

9. A parallel LC circuit resonant at 20 kHz has a 50 mH inductor, an impedance of 60 K and a Q of:

   a. 2.5.
   b. 9.5.
   c. 70.
   d. 80.

10. A parallel resonant circuit has a Q of 50, an L of 18 mH and a C of 880 pf. Its bandwidth is:

   a. 158 Hz.
   b. 900 Hz.
   c. 68 Hz.
   d. 800 Hz.

KEY TERMS

1. BAND PASS

   The range of frequencies between the half power points of the tuned circuit response curve. It is expressed as $BP = f_2 - f_1$.

2. BAND STOP

   The range of frequencies between the half power points of the tuned circuit that are blocked. The blocked range of frequencies is equal to $f_2 - f_1$ where f_2 is the upper half power point and f_1 the lower.

3. BANDWIDTH

   The range of frequencies of a tuned circuit that fall between the half power points. It is expressed as $BW = f_2 - f_1$.

4. CIRCUIT Q

   While the Q of an inductor may be high, when connected into a circuit, the circuit elements will often degrade the inductor Q. This results in a "circuit Q" that is lower than the inductor Q.

5. LINE CURRENT

   The current fed to a parallel resonant LC tank circuit by the source generator. It is lowest at resonance and increases as the tank circuit is tuned off-resonance. The line current is also affected by the circuit Q, increasing as the Q decreases.

6. PARALLEL RESONANCE

   The state that exists in a parallel circuit consisting of an ac voltage source, capacitance and inductance when the frequency is such that X_L equals X_C.

7. PHASOR

   Also known as a Vector, it is a quantity that has magnitude and direction and is shown by line segments.

8. RADIATION

   The movement of radio energy through the air or space. The radio energy consists of an electromagnetic field.

9. RESONANCE CURVE

A plot of frequency versus voltage or current or impedance of an LC circuit. The normal response is called a Bell Curve.

10. RESONANT FREQUENCY

The frequency at which X_L equals X_C in an LC circuit.

11. TANK CIRCUIT

An LC circuit capable of storing and exchanging energy between the L and C components.

12. TANK CURRENT

The current flow exchanged between the inductor and capacitor in a tank circuit.

13. TUNING RANGE

The highest and lowest frequency a tank circuit can be tuned to when one of the tank components (L or C) is variable.

LC Radio Receiver 10

OBJECTIVES

When you finish this experiment you will be able to:

1. Explain how a resonant LC circuit can select a single radio signal from among many.
2. Wire a tuned circuit and view the radio transmission signals on an oscilloscope screen.
3. Calculate the inductance of the radio coil on the trainer panel.
4. Wire and test a one transistor radio receiver.
5. Add an operational amplifier to the output of the radio circuit.
6. Add a power amplifier to the output of the operational amplifier.
7. Wire a simple Public Address system.

DESCRIPTION

In a previous experiment, the parallel LC circuit or TANK circuit was used to select or filter a particular small band of frequencies. It was also demonstrated that the resonant circuit could provide an output signal even when not directly connected to the ac signal source. This concept is illustrated in Figure 1 and is the basis of radio transmission and reception.

Many radio stations transmit signals on different frequencies, as shown in Figure 1. All the signals are picked up by the receiving antenna that is connected to the RESONANT CIRCUIT. The only output signal will be the one the resonant circuit is tuned to, f2 in this example. The standard AM (amplitude modulation) broadcast radio frequency (RF) range is from 540 kHz to 1610 kHz. The highest frequency used in previous experiments was 100 kHz. To operate at these higher radio frequencies, it is necessary to use smaller values of L and C in the parallel resonant circuit.

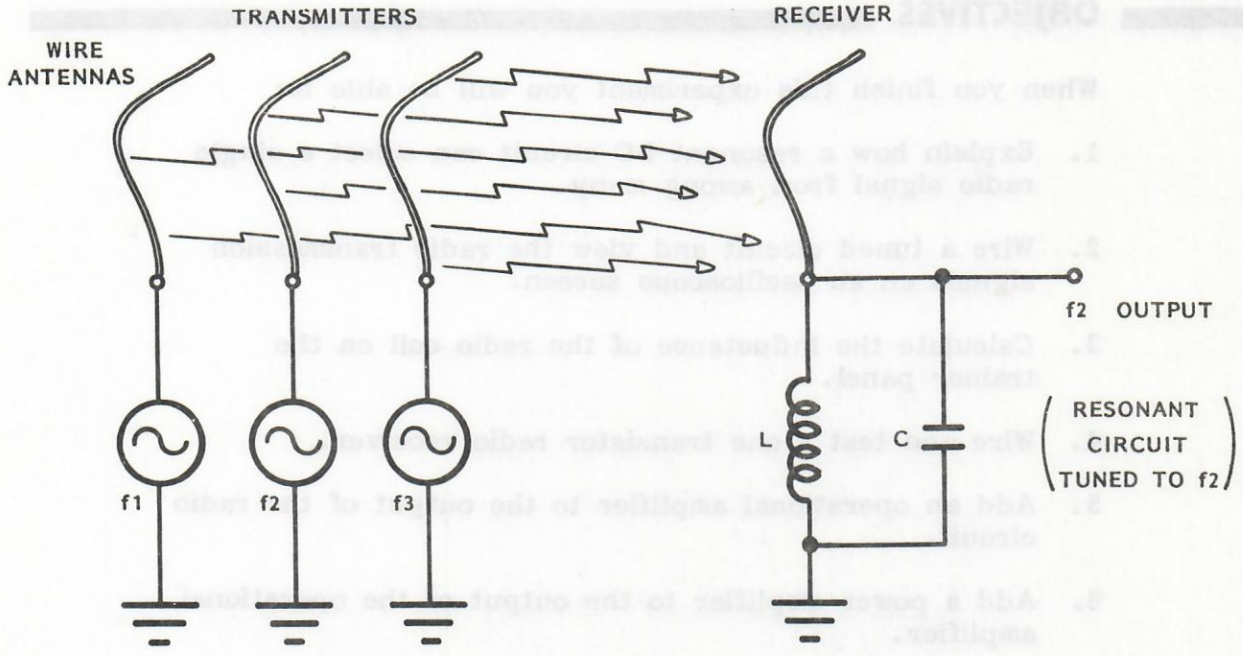


Figure 1 - Basic concept of radio transmission and reception.

RF TRANSFORMER

A transformer, marked T2, on the Ed-Lab panel is a low value inductor useful for radio receiver circuits. In addition to having a small inductance value, it is "slug-tuned" so that the inductance can be varied to receive different radio stations. The maximum inductance value of T2 will be measured in this experiment. Consider an ac signal applied to a resonant circuit as shown in Figure 2, with an unknown value of L.

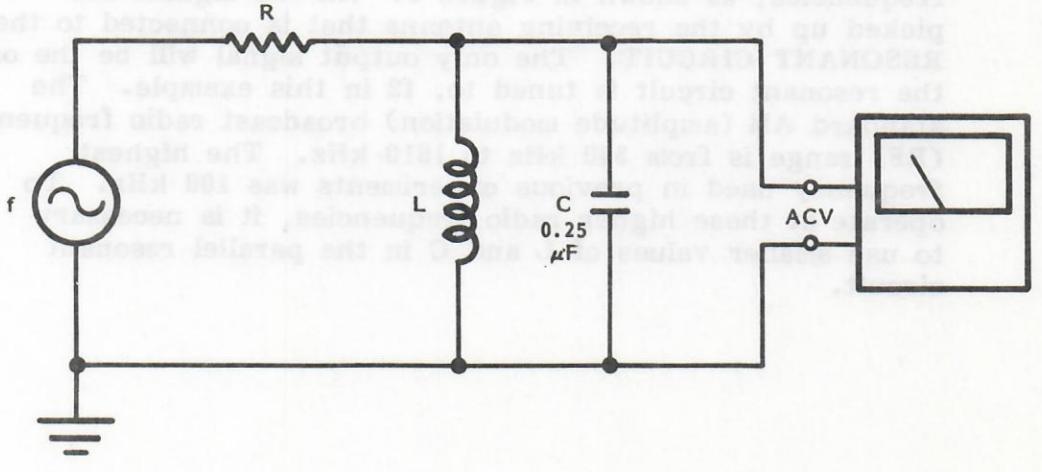


Figure 2 - Resonant circuit and ac meter.

The frequency of the signal source is varied and, when f is at the resonant frequency of the tank circuit, the ac voltage will peak or be at maximum. This frequency is noted as f_r.

The equation for resonance is:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

When f_r and C are known and it is necessary to determine the value of L, the equation must be transposed to solve for L. The equation is first squared resulting in:

$$f_r^2 = \frac{1}{(2\pi)^2\ LC}$$

Solving for L:

$$\boxed{L = \frac{1}{(2\pi)^2\ f_r^2\ C}}$$

If C is known to be 0.25 μf and f_r is measured to be 20 kHz, then, using a calculator to find L, we have:

$$L = \frac{1}{(6.28)^2(20 \times 10^3)^2(0.25 \times 10^{-6})}$$

$$L = \frac{1}{(6.28)^2(4 \times 10^8)(0.25 \times 10^{-6})}$$

$$L = \frac{1}{(6.28)^2(100)} \text{ henries}$$

To find L in microhenries, multiply by 10^6:

$$L = \frac{1{,}000{,}000}{(6.28)^2(100)}$$

$$L = \frac{10{,}000}{39.44}$$

$$\boxed{L = 253\ \mu H}$$

RADIO TUNING

If a capacitor of 220 pF is used with the 253 μH inductor, the resonant frequency of the tank circuit will be:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{6.28\sqrt{(253 \times 10^{-6})(220 \times 10^{-12})}}$$

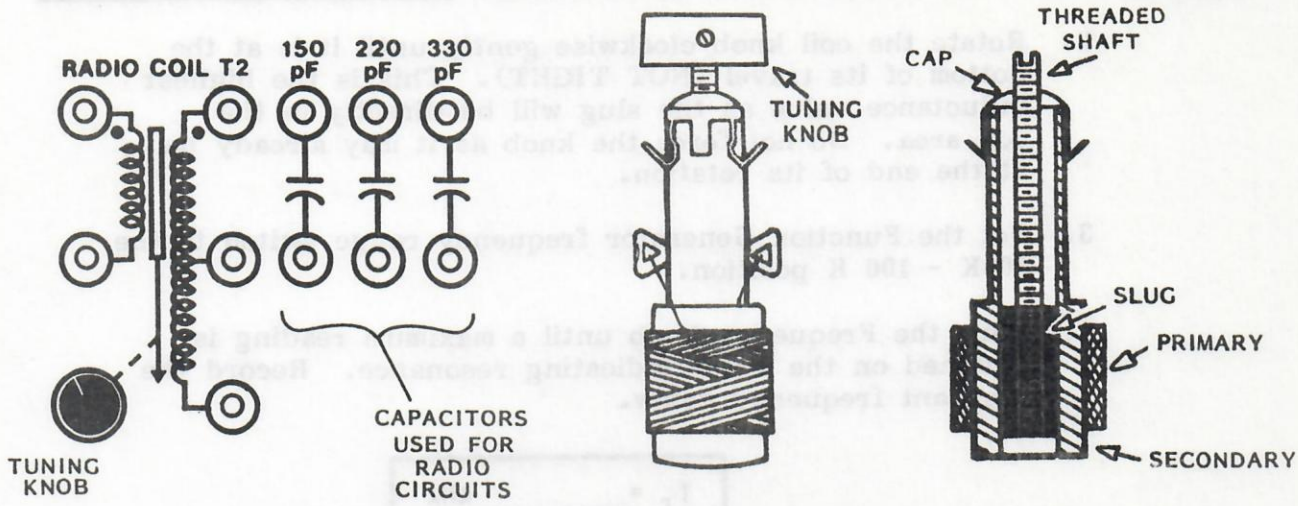
$$= \frac{1}{6.28\sqrt{(253)(220) \times 10^{-18}}}$$

$$= \frac{10^9}{6.28\sqrt{55{,}660}} = \frac{1000}{1481.6} \times 10^6$$

$$\boxed{f_r = 674{,}945\ Hz}$$

This frequency, approximately 675 kHz, is at the low end of the AM radio broadcast band.

The RF TRANSFORMER symbol on the trainer panel is shown in Figure 3.



(a) T2 PANEL SYMBOL (b) PICTORIAL SKETCH (c) CROSS SECTION CONSTRUCTION

Figure 3 - RF Transformer on the trainer panel.

As the tuning knob is rotated, it moves the powdered iron slug or core in the coil and varies the inductance value. This changes the resonant frequency and thus will change the radio station being received when T2 is wired into a radio receiver resonant circuit.

PROCEDURE

1. Wire the resonant circuit shown in Figure 4.

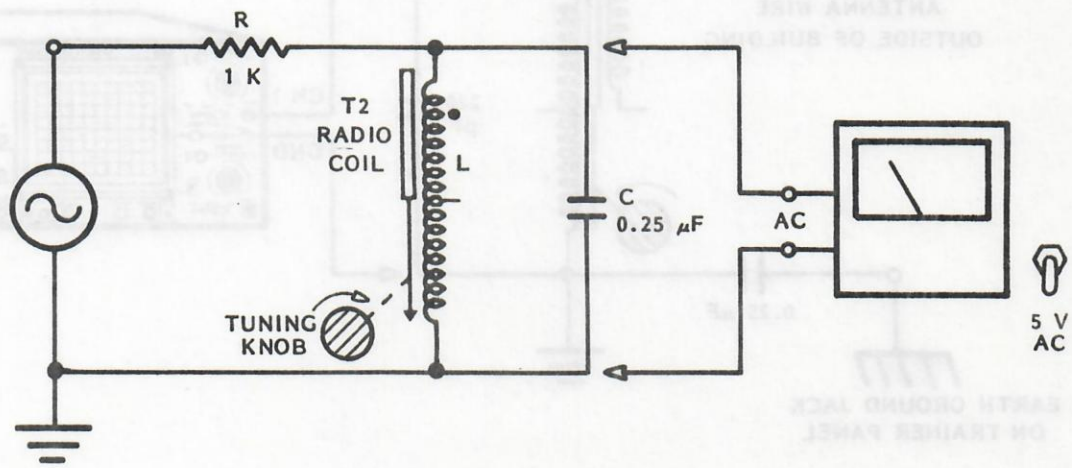


Figure 4 - Resonant circuit test; EXPERIMENT.

10.1 CALCULATING L OF RF INDUCTOR

2. Rotate the coil knob clockwise gently until it is at the bottom of its travel (NOT TIGHT). This is the highest inductance value as the slug will be directly in the coil area. Do not force the knob as it may already be at the end of its rotation.

3. Set the Function Generator frequency range switch to the 10 K - 100 K position.

4. Vary the Frequency knob until a maximum reading is obtained on the meter indicating resonance. Record the resonant frequency below.

f_r = _____ kHz

The frequency should be very close to 20 kHz and so the inductance is near 250 μH as calculated earlier in the discussion.

10.2 RADIO SIGNALS

5. Wire the basic radio receiver resonant circuit as shown in Figure 5.

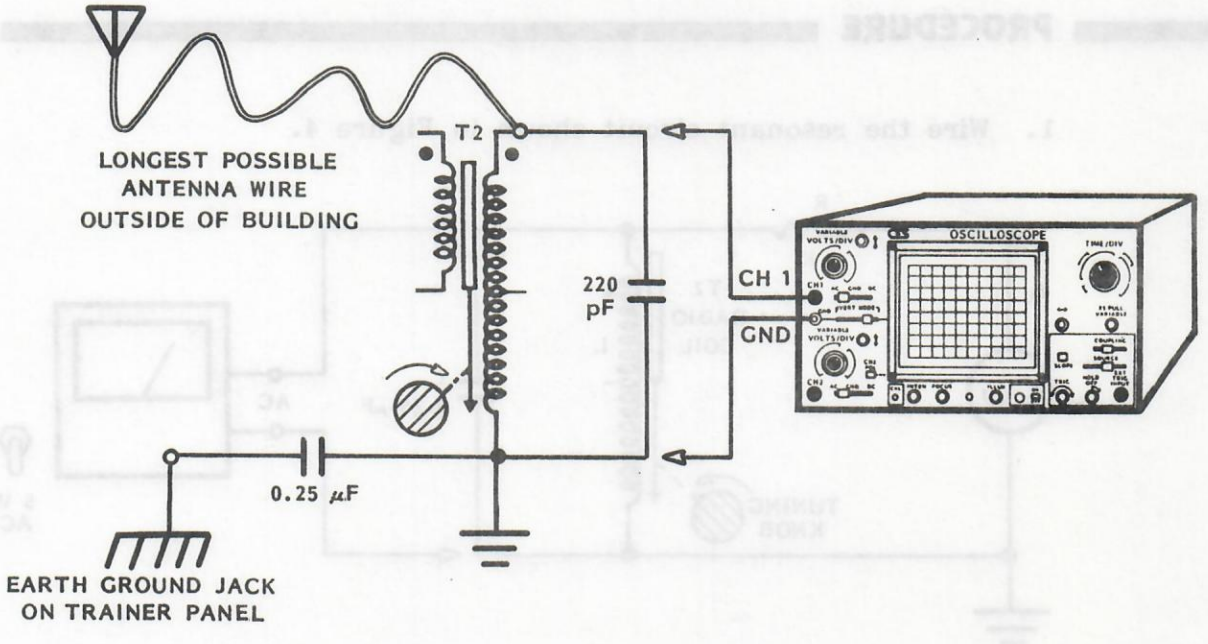


Figure 5 - Resonant circuit for the AM radio band; EXPERIMENT.

6. Connect an antenna wire approximately 20 to 50 feet long and if you are in a steel building, drop the wire out a window or spread it on the ground. If the antenna is too short, or inside a steel frame structure, there will not be enough of a radio signal to produce an output.

7. Turn the Ed-Lab trainer power OFF. Keep the line cord plugged-in.

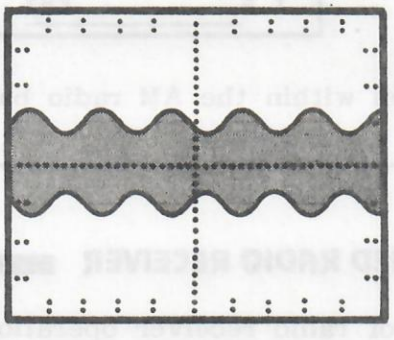
8. Set the oscilloscope as follows:

CH 1 V/DIV	5 mV
VERT MODE	CH 1
SYNC SOURCE	CH 1
TIME/DIV	20 μS

9. The connection between the trainer ground and the earth ground jack, using the 0.25 μF capacitor as shown in Figure 5, often helps to increase the signal strength. It also helps reduce any stray pickup of 60 Hz signals radiated from the power lines and lighting fixtures in the building.

10. Observe the oscilloscope while slowly rotating the tuning knob counter clockwise, looking for signals to appear and disappear on the screen. Count the number of "stations" that you pick up over the full tuning range.

    If the antenna is long enough and there are strong broadcasting stations in the area, you will be able to see RF signals on the screen similar to that shown below:



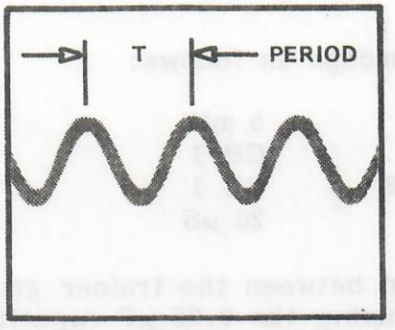
How may different station signals did you observe on the screen? _____

Do not make the change now, but you may be able to receive additional stations by changing the tuning range of the resonant circuit. This is done by using a 330 pF (lower frequencies) or a 150 pF (higher frequencies) instead of 220 pF.

The source of power for any signal received must be the local broadcast station transmitting antenna because the Ed-Lab trainer power is OFF.

11. Adjust the tuning knob to result in a strong signal on the oscilloscope screen. Change the TIME/DIV switch from 20 μS to 0.5 μS to view the radio frequency signal.

Measure the period of one sine wave as shown and record it below.



T = _____ μS

Calculate the station frequency from:

$$f = \frac{1}{T}$$

f = _____ kHz

Is the station within the AM radio band (535 to 1610 kHz)?

_____

10.3 BASIC TUNED RADIO RECEIVER

12. The theory of radio receiver operation involves advanced topics such as:

RADIO FREQUENCY AMPLIFIERS
DETECTORS
AUDIO FREQUENCY VOLTAGE AMPLIFIERS
POWER AMPLIFIERS

Although these and other topics have not yet been covered and experiments with transistors have not been performed, the radio circuit can be wired and several broadcast stations may be heard.

Wire the circuit shown in Figure 6.

Transistor Q5 "detects" the RF signal, removing the RF and providing an audio frequency (AF) output signal. This AF signal is heard in the earphones. Note that in Figure 6, the antenna is connected to A on T2 instead of B. This provides greater selectivity between stations, but reduced signal strength and can only be used in areas where the signals are strong. To obtain a stronger signal, you may want to move the antenna to Point B.

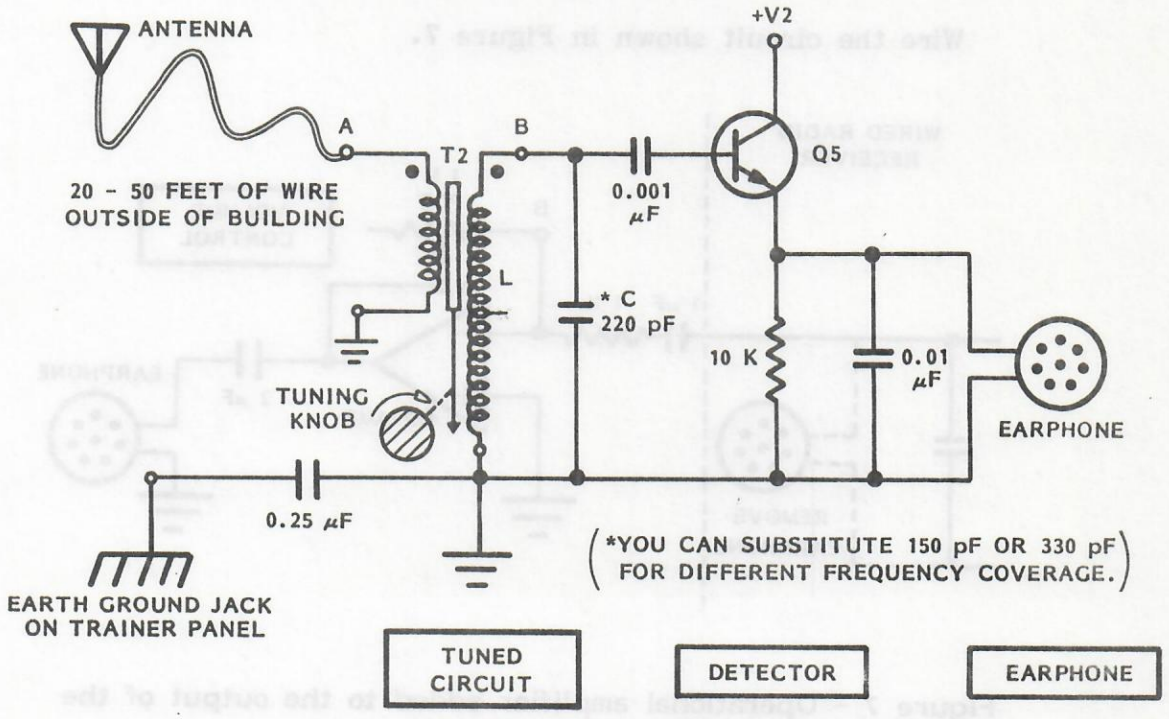


Figure 6 - LC tuned radio receiver EXPERIMENT.

13. Carefully vary the tuning knob while listening to the earphone for station signals. The volume and the number of stations received will be dependent upon the length of the antenna, the longer the better.

How may stations could you hear? _____

You can substitute the 150 pF or 330 pF capacitors for the 220 pF across the inductor for different frequency coverage.

You can connect the antenna to point B, again, instead of point A for a stronger signal if necessary, however, there is less separation between stations.

You can proceed to the amplifier experiment in the next steps for improved performance.

10.4 AUDIO AMPLIFIER (OPTIONAL)

14. The operational amplifier will be added to the output of the receiver to increase the signal strength.

Wire the circuit shown in Figure 7.

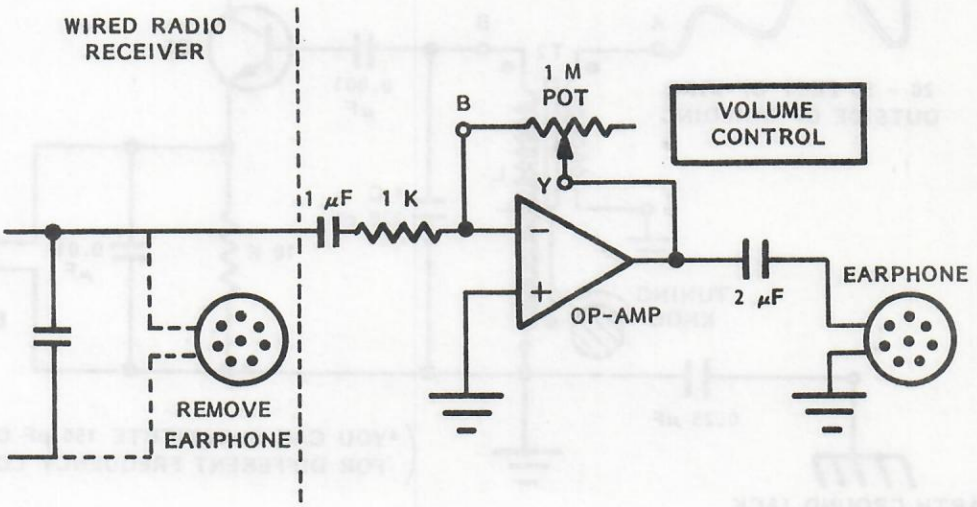


Figure 7 - Operational amplifier added to the output of the radio; EXPERIMENT.

15. Move the earphone to the output of the operational amplifier, (OP-AMP) and test the radio receiver performance.

Are the stations heard at a louder volume?

How may stations can you receive?

10.5 POWER AMPLIFIER (OPTIONAL)

16. Add the power amplifier circuit to the radio receiver to drive the loudspeaker.

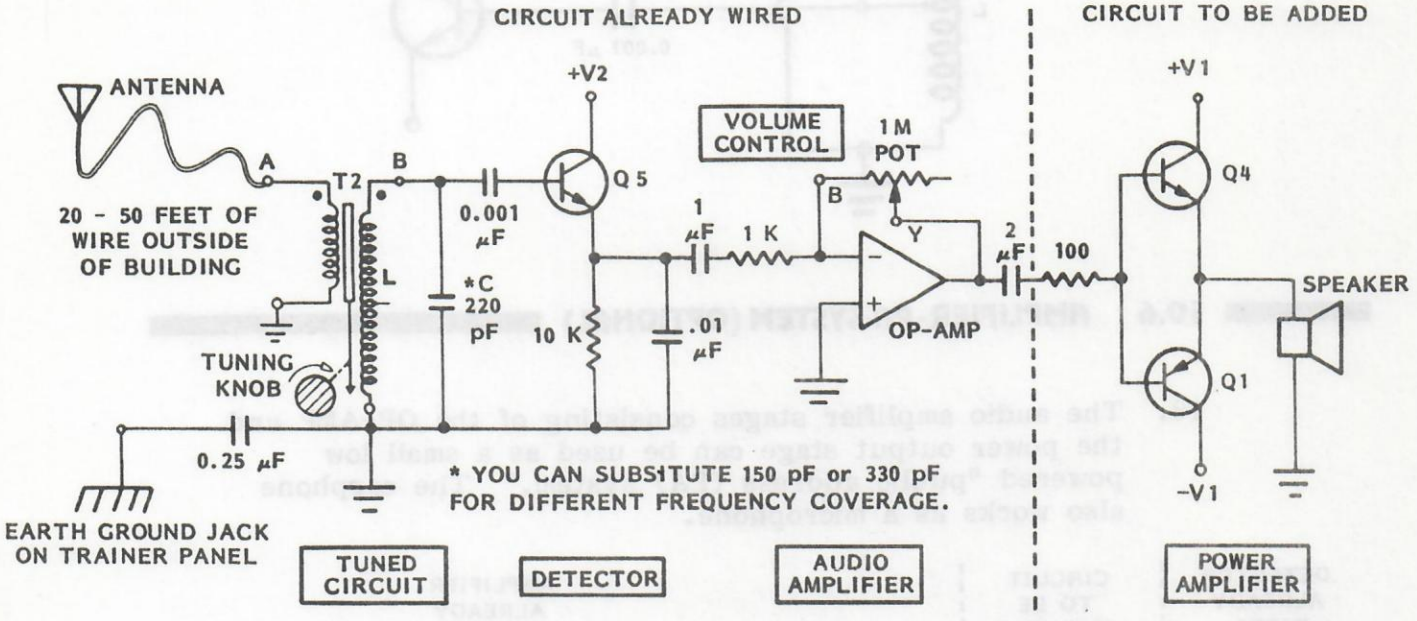


Figure 8 - Power amplifier circuit EXPERIMENT.

17. Test the radio receiver with the power amplifier.

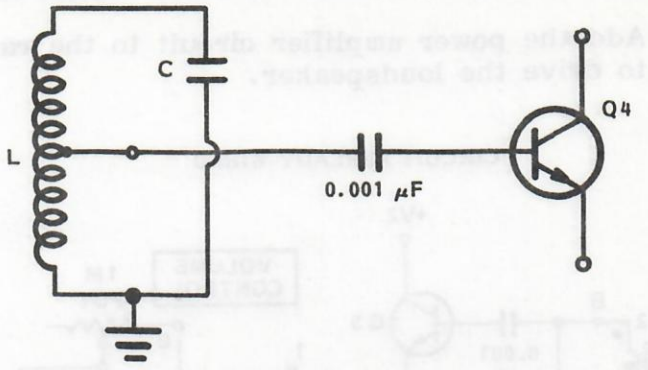
Various methods can be used to improve performance, that is, receive more stations and develop a louder signal.

a. To increase the audio level you can "short out" the 1 K input resistor to the OP-AMP (Figure 7 and 8).

b. To increase the audio volume more, you can place a 1 meg or 4.7 meg resistor in series with the 1 meg pot in the OP-AMP circuit (Figure 7 and 8).

c. You can change the capacitor (150 pF or 220 pF or 330 pF to vary the frequency tuning range.

d. To decrease interference between stations (improve selectivity) when you have strong station signals, remove the wire connecting the 0.001 μF capacitor from the top of the LC circuit and connect the lead to the tap on the coil as shown on the next page:



10.6 AMPLIFIER-PA SYSTEM (OPTIONAL)

18. The audio amplifier stages consisting of the OP-AMP and the power output stage can be used as a small low powered "public address (PA) system." The earphone also works as a microphone.

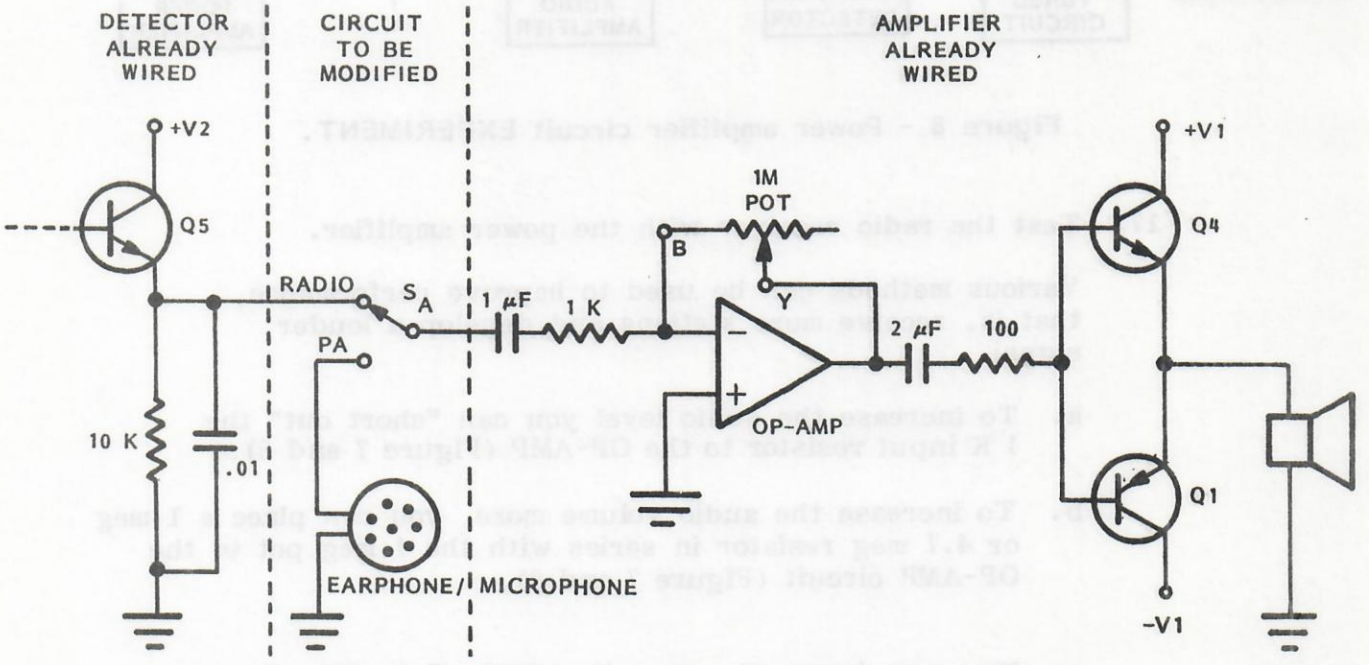


Figure 9 - Radio - PA system EXPERIMENT.

19. Set switch SA UP for radio reception and test for normal operation.

Set switch SA DOWN for PA operation. Speak into the Earphone/Microphone, holding the microphone very close to your lips for best pick up.

CONCLUSIONS

We have learned from this experiment that:

A parallel resonant tuned circuit can be used to select a signal of one frequency and reject most of the other signals.

A primary winding wound on the coil of the tuned circuit acts to transfer the signals to the secondary winding. It acts as a transformer.

The resonant frequency of the tuned circuit is determined by the LC combination according to:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The AM broadcast band ranges from a low frequency of 540 kHz to a high of 1610 kHz.

The function of the detector circuit, Q4 in this receiver, is to separate the audio signal, AF, from the radio signal, RF, and provide the audio, or sound as the output.

The audio output signal from the detector can be further strengthened by the addition of an audio amplifier (Figure 7).

The audio signal may be used to drive a speaker if an audio power amplifier is added as in Figure 8.

A simple receiver of this type needs a strong RF input signal that can be obtained from a long antenna or a powerful local radio station.

The combination of the audio voltage amplifier and power amplifier can be used as a small, simple, public address system.

ASSIGNMENT

Answer the following multiple choice questions.

1. A variable inductor and a parallel capacitor can tune to a low frequency of 600 kHz. To lower the tuning range to 540 kHz it is necessary to:

   a. reduce the value of L by withdrawing the slug.
   b. increase the value of L by withdrawing the slug.
   c. increase the value of the parallel capacitor.
   d. decrease the value of the parallel capacitor.

2. A parallel tuned LC circuit could separate stations better if the:

   a. values of L and C were increased.
   b. coil used has a low dc resistance and thus a lower Q.
   c. values of L and C were decreased.
   d. coil used has a low dc resistance and thus a higher Q.

3. An LC tuned circuit consists of a 250 μH inductor and a 200 pF capacitor. The resonant frequency is closest to:

   a. 712 kHz.
   b. 712 mHz.
   c. 712×10^{13} Hz.
   d. 4.47 mHz.

4. The highest frequency an LC tank circuit can tune in is 1400 kHz. In order to tune to 1600 kHz:

   a. the parallel capacitance should be reduced.
   b. the parallel capacitance should be increased.
   c. a capacitor must be placed in parallel with the existing capacitor.
   d. an inductor must be placed in series with the existing inductor.

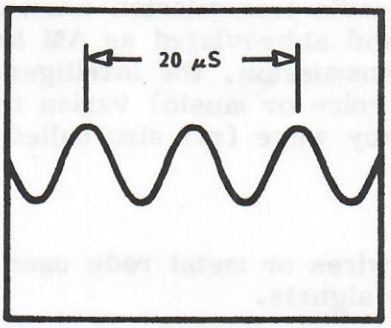
5. The longer the antenna connected to the radio constructed in this experiment the:

   a. More radio stations it is possible to pick up.
   b. stronger the radio signal will be.
   c. both a and b.
   d. neither a or b.

6. A 16 mH inductor in a parallel resonant circuit must tune to 2.68 kHz. The required parallel capacitor value is:

   a. 2.2 μF.
   b. 0.22 μF.
   c. 0.59 μF.
   d. 1.4 μF.

7. The radio signal received and observed on the oscilloscope screen displays the waveform shown below:



The frequency of the signal is:

a. 50 kHz.
b. 100 kHz.
c. 1×10^5 kHz.
d. none of the above.

8. The purpose of the operational amplifier in the two stage radio receiver is to:

a. act as a detector.
b. amplify the RF signal.
c. amplify the audio signal.
d. act as a power amplifier.

KEY TERMS

1. AM RADIO

   A system of radio transmission known as "Amplitude Modulation" and abbreviated as AM Radio. Using this method of transmission, the intelligence to be transmitted (voice or music) varies the amplitude of the radio frequency wave (rf) also called the "carrier."

2. ANTENNA

   A system of wires or metal rods used to transmit or receive radio signals.

3. BROADCAST BAND

   The range of frequencies from 540 Hz to 1610 kHz over which amplitude modulated radio signals are broadcast for entertainment purposes.

4. DETECTOR

   A circuit in a radio receiver that separates the audio intelligence from the carrier wave. Also called a "demodulator."

5. EARPHONE

   A device that converts electrical impulses to equivalent sound waves. It is placed over the ear for loudest sound.

6. FREQUENCY

   The number of recurrences of a cycle in one second, measured in Hertz.

7. MICROPHONE

   A device that converts sound energy into an equivalent electrical energy.

8. OP-AMP

   Abbreviation for "Operational Amplifier." An amplifier originally intended to perform mathematical operations is also used for other applications, one of which is an audio signal amplifier.

9. OPERATIONAL AMPLIFIER

   See 8, Op-Amp, above.

10. POWER AMPLIFIER (PA)

An amplifier that delivers power to a load. In this experiment the power amplifier delivered power to drive a speaker.

11. PUBLIC ADDRESS SYSTEM

Abbreviated as PA System, it consists of a microphone, power amplifier and one or more speakers. It is used to address large audiences.

12. RADIO FREQUENCY (RF)

A frequency at which electromagnetic radiation into air and space occurs. May be as low as 10 kHz up to 300 gHz.

13. RADIO RECEIVER

An electronic system that includes an antenna, detector circuit, amplifiers and a device to convert the electrical impluses to equivalent sound such as a speaker. Most receivers have a system of tuning to select the desired radio transmission.

14. RADIO TRANSMITTER

A group of circuits, microphone and antenna that enables the transmission of a radio frequency signal.

15. RESONANT CIRCUIT

A circuit that contains both L and C and is used to select a single frequency, the resonant frequency, where X_L equals X_C. The resonant frequency can be varied by changing the value of L or C.

RL Filter Circuits 11

OBJECTIVES

When you finish this experiment you will be able to:

1. Define the function of a filter circuit.
2. Define the functions of a low and high pass filter.
3. Explain the operation of RL high and low pass filters.
4. Wire and test the operation of low and high pass filter circuits.
5. Plot the frequency response curve of an RL filter on semi-log graph paper.
6. Calculate the cut-off frequency of an RL filter.
7. Measure the cut-off frequency of an RL filter.

DESCRIPTION

AC signal voltages in electronic systems are composed of many frequencies. In any given system, it is often necessary to separate these frequencies using circuits called FILTERS. A filter circuit is a group of R, L and C components wired so that one group or range of frequencies appears at the output while all other frequencies are blocked.

In previous experiments, the ac currents, voltages and impedances were discussed. The values of I, V and Z were shown to be frequency dependent. As a result, for fixed component values, the filter will produce varying output levels for varying input frequencies. This is shown in Figure 1(a) and 1(b) for a circuit called a LOW PASS RL FILTER.

A low pass filter circuit passes low frequencies and blocks high frequencies. As shown in Figure 1, one type of low pass filter is made with R and L components wired in series where the output is taken across R. When the input frequency is low, X_L is low and most of the input voltage appears across R, the output.

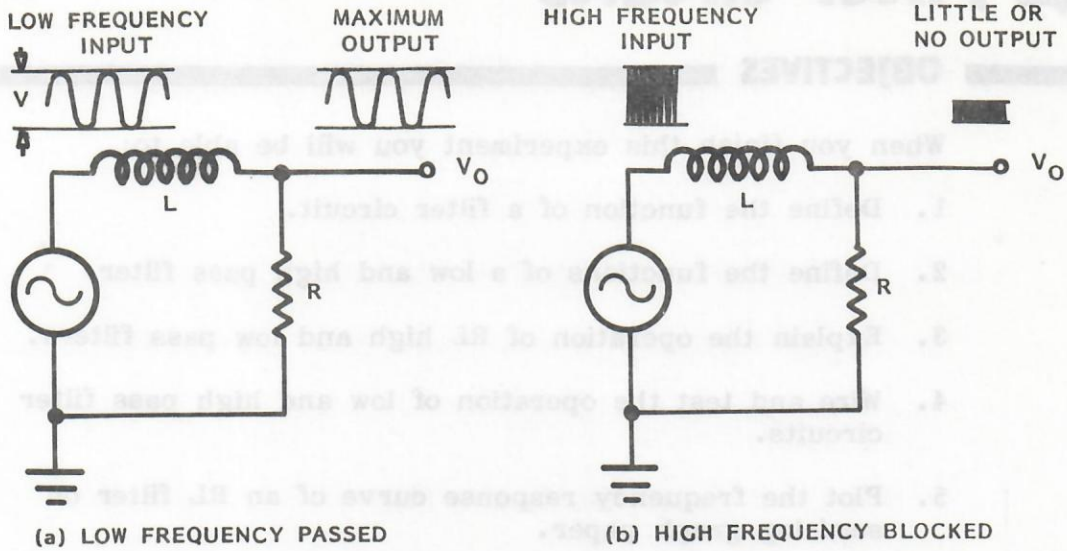


Figure 1 - Low pass RL filter circuit.

As the input signal frequency increases, the value of X_L increases and the voltage division between the X_L and R changes. More voltage appears across L and less appears across R which is the output. As the frequency continues to rise, less and less voltage appears at the output. The result is a low pass filter circuit.

HIGH PASS RL FILTER

By reversing the positions of R and L in the filter circuit, as shown in Figure 2, and taking the output across the inductor, the behavior of the circuit changes. In this configuration, the output voltage versus frequency relationship is a HIGH PASS FILTER. This means that low frequencies are blocked while high frequencies appear at the output.

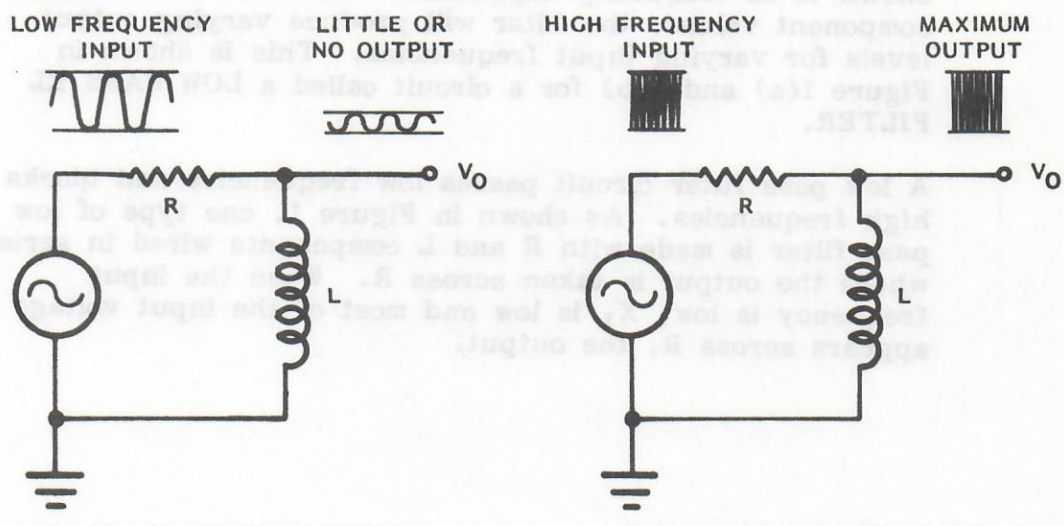


Figure 2 - High pass RL filter circuit.

For the high pass RL filter circuit in Figure 2, when the input frequency is low, X_L is low. Most of the signal voltage will be across R and not appear at the output. As the input signal frequency is increased, the inductive reactance of L increases. This results in an increase in output voltage. If the frequency rises high enough, the output voltage will almost equal the input voltage.

FREQUENCY RESPONSE

The output voltage versus the input frequency graph or plot of a filter is called the FREQUENCY RESPONSE. It is displayed graphically with the voltage output plotted on the Y axis (vertical) and the frequency plotted on the X axis (horizontal.) As the frequency is increased, the output voltage decreases in the low pass filter as in Figure 3(a). As the frequency is increased, the output voltage increases in the high pass filter as in Figure 3(b).

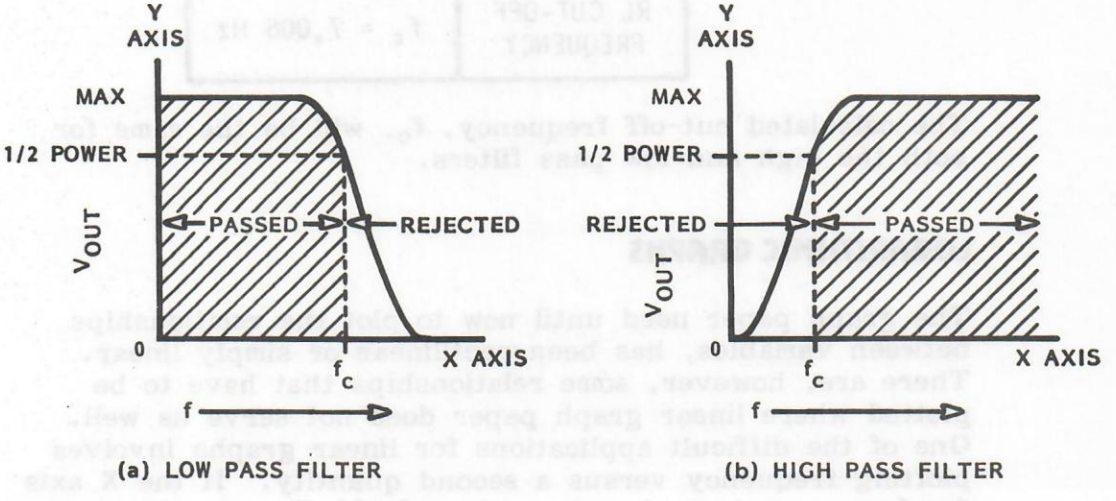


Figure 3 - Filter frequency response curves.

The CUT-OFF frequencies, f_c, just as for the resonance curves of the earlier experiments, are located at the half power points, $1/\sqrt{2}$ or 0.707 times V_{MAX}. The half power point occurs at the frequency where the reactance of the inductor, X_L, is equal to the circuit resistance, R, or:

AT HALF POWER $\quad X_L = R$

Expanding this results in:

$$2\pi f_c L = R$$

Transposing to solve f_c, we have:

RL CUT-OFF FREQUENCY	$f_c = \frac{1}{2\pi} \times \frac{R}{L}$

Given an RL circuit where R = 2.2 K and L = 50 mH, the cut-off frequency is:

$$f_c = \frac{R}{2\pi L}$$

$$= \frac{2.2 \times 10^3}{(6.28)(50 \times 10^{-3})}$$

RL CUT-OFF FREQUENCY	f_c = 7,006 Hz

The calculated cut-off frequency, f_c, will be the same for both the high and low pass filters.

LOGARITHMIC GRAPHS

The graph paper used until now to plot the relationships between variables, has been rectilinear or simply linear. There are, however, some relationships that have to be plotted where linear graph paper does not serve us well. One of the difficult applications for linear graphs involves plotting frequency versus a second quantity. If the X axis for frequency is assigned a value of 100 Hz per division, to plot a frequency coverage of 100 Hz to 50 kHz would require an X axis of 500 divisions. Using 10 divisions per inch would require a graph at least 50 inches long. This is too long to be practical. If we were to reduce the size of the graph by making each division 1 kHz, the curve variations between 0 Hz to 1 kHz would be completely lost.

The solution to this problem is to use "non-linear" or LOGARITHMIC graph paper. A comparison between linear and logarithmic (called LOG for short) scales is shown in Figure 4. Note that the log scale starts from 1, not 0.

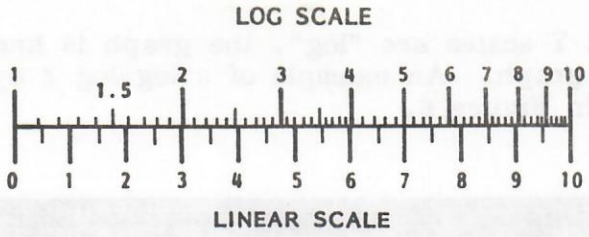


Figure 4 - Comparison of linear and log graph scales.

To extend the log graph range beyond 1 to 10, the same scale markings are repeated but numbered from 10 to 100. A third set of scale markings would be numbered from 100 to 1000. Each set of markings is called a CYCLE and a 3 cycle log scale is shown in Figure 5. The first cycle starts at 100 Hz and the last cycle ends at 100 kHz.

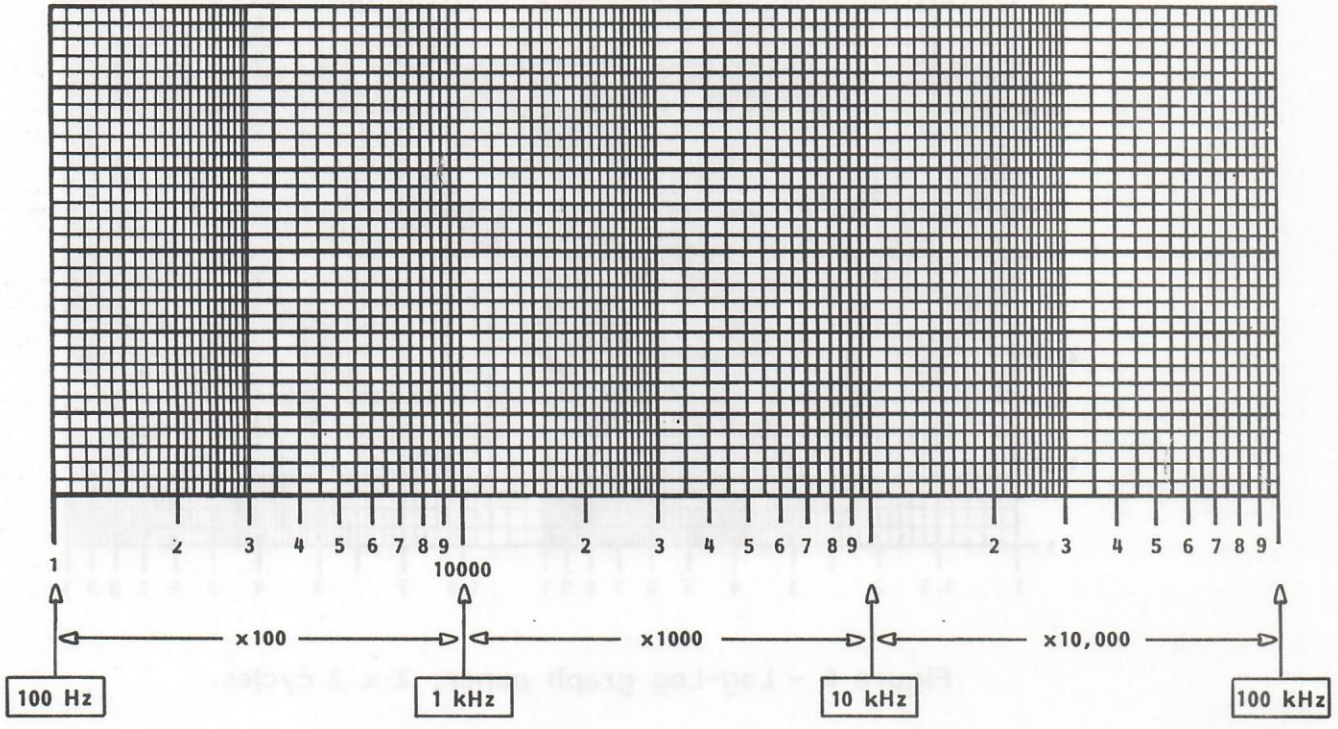


Figure 5 - Three cycle log scale calibrated from 100 to 100,000 Hz.

The Y or vertical axis of the graph can have a linear scale, as shown in Figure 5, or it can also be calibrated logarithmically. When the Y axis is linear and the X axis is "log", the graph is called a SEMI-LOG graph. Thus, the graph of Figure 5 is a "3 cycle semi-log graph." When both

the X and Y scales are "log", the graph is known as a LOG-LOG graph. An example of a log-log 2 by 2 cycle graph is shown in Figure 6.

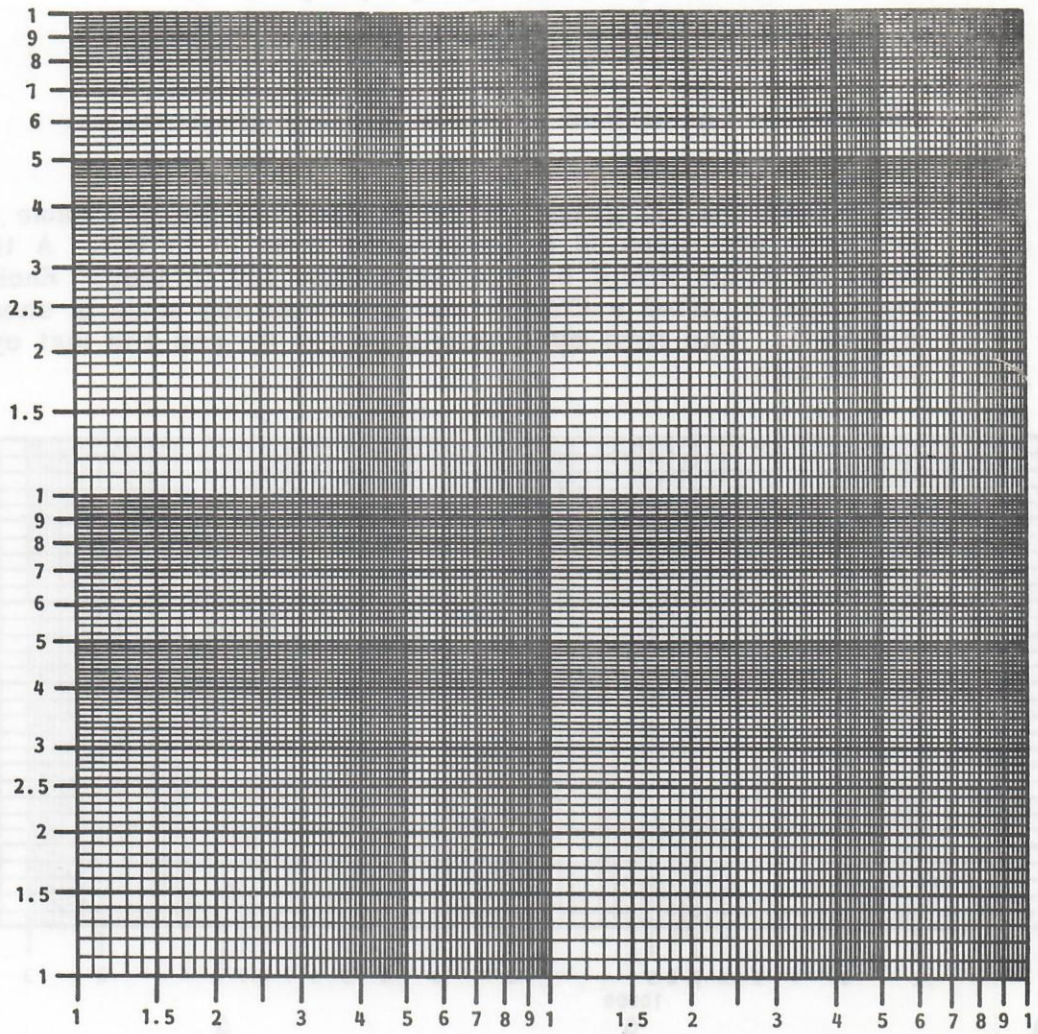


Figure 6 - Log-Log graph paper, 2 x 2 cycles.

LOW PASS FILTER EXPERIMENT

In this experiment you will wire a low pass RL filter and measure the output voltage over a frequency range of 100 Hz to 100 kHz. You will then plot the measurements on a semi-log graph. The half power point frequency, f_c, will be determined from the plot and compared to the calculated values. The same procedure will then be followed for an RL high pass filter.

PROCEDURE

1. Wire the low pass RL filter shown in Figure 7.

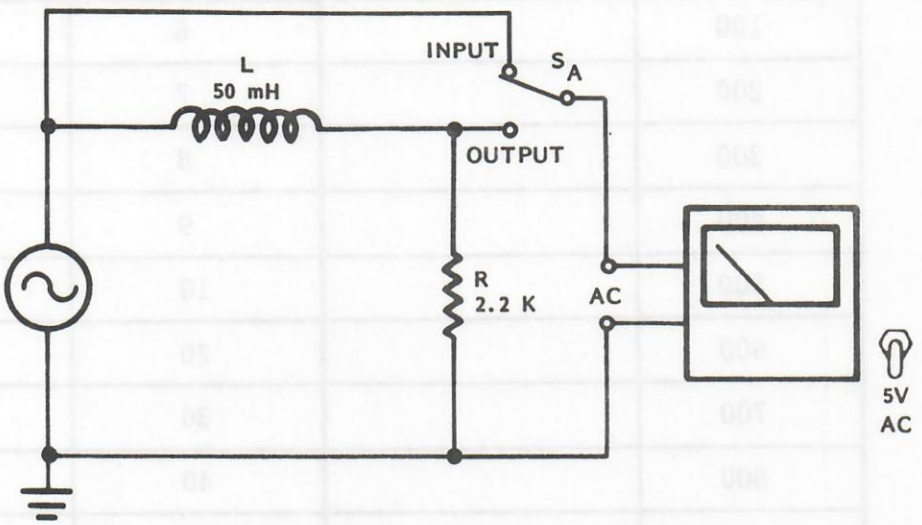


Figure 7 - Low pass filter EXPERIMENT.

11.1 LOW PASS FILTER

2. Set switch SA DOWN to measure the output voltage.

   Set the Function Generator frequency to 100 Hz.

3. Adjust the SINE AMPL. control for an output of 3 volts. It is not necessary to monitor the INPUT voltage when using the Ed-Lab Function Generator. If using another external generator it may be necessary to measure and keep the input voltage constant.

4. Switch to the 1 kHz - 10 kHz range of the Function Generator and vary the frequency from 1 kHz to 10 kHz and observe the general variation in output level.

   Does the circuit exhibit the characteristics of a low pass filter? How?

   _____

   _____

5. Read the output voltages for the frequencies listed in Table 1 and enter the readings.

f (Hz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
100		6	
200		7	
300		8	
400		9	
500		10	
600		20	
700		30	
800		40	
900		50	
1000		60	
2000		70	
3000		80	
4000		90	
5000		100	

TABLE 1 - V_{OUT} versus frequency for the low pass filter.

11.2 FREQUENCY RESPONSE CURVE

6. Plot the results listed in Table 1 on the three cycle semi-log graph of Figure 8.

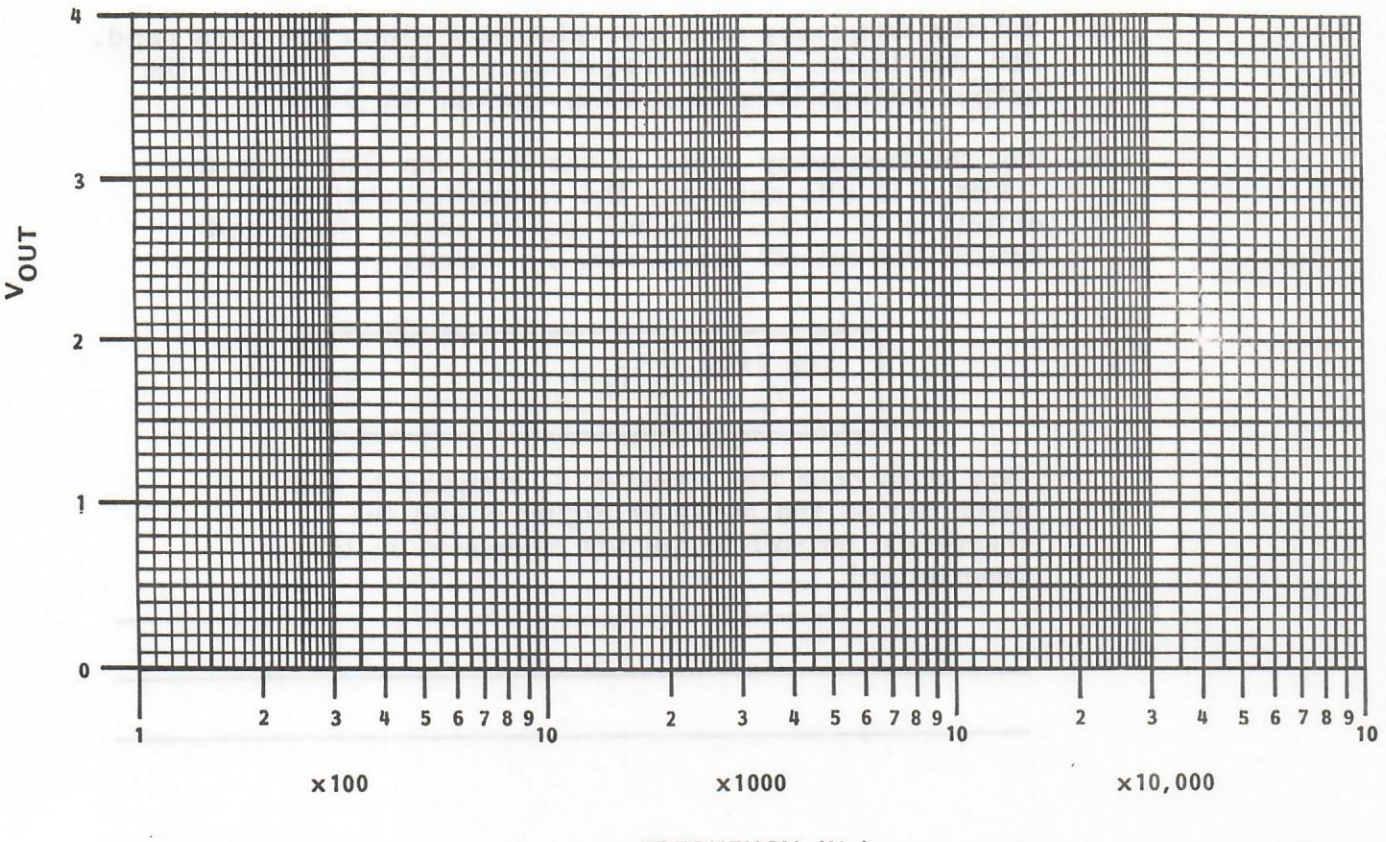


Figure 8 - Plot of output versus frequency for the RL low pass filter.

7. Circle the curve at the half power point where it intersects the 2.1 volt (3 x 0.707) level.

8. The frequency at which the curve intersects the half power point is the cut-off, f_c. Read the graph of Figure 8 and enter this frequency below.

LOW PASS f_c	f_c = _____ Hz

How close is the measured value of f_c compared to the theoretical f_c of 7006 Hz calculated in the description?

_____

11.3 SIMPLIFIED CUT-OFF FREQUENCY MEASUREMENT

9. Measuring the cut-off frequency does not require plotting the entire response of the low pass filter. All that is necessary is to use 2 points as follows:

a. Set the frequency at a low value well within the pass band. For this filter, set the frequency to 500 Hz. Adjust the output voltage level to 3 volts (switch SA DOWN).

b. Set the frequency range of the Function Generator to 1 kHz - 10 kHz and vary the frequency until the output is 2.1 volts, the half power point. Read and record the cut-off frequency, f_c, below.

LOW PASS f_c	f_c = _____ Hz

How close does this value of f_c compare to that measured on the curve in Figure 8 and the theoretical cut-off frequency calculated in the description?

_____

_____

_____

11.4 HIGH PASS RL FILTER

10. Remove the existing wiring and wire the high pass RL filter shown in Figure 9.

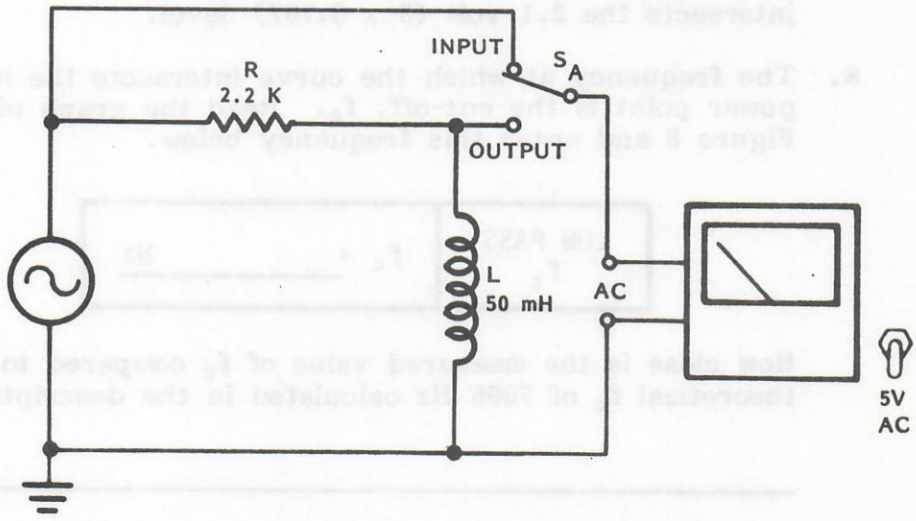


Figure 9 - High pass filter EXPERIMENT.

11. Set the Function Generator to a high value in the pass band; 50 kHz.

    Set Switch A DOWN to read the output and adjust the level to 3 volts.

12. Reduce the frequency until a reading of 2.1 volts (half power) is obtained. Read this cut-off frequency, fc, and record it below.

HIGH PASS f_c	f_c = _____ Hz

11.5 HIGH PASS RESPONSE CURVE (OPTIONAL)

13. Read the output voltages for the frequencies listed in Table 2 and enter the readings. It is not necessary to check the input voltages if the Ed-Lab 651 Function Generator is used.

f (Hz)	V_{OUT} (VOLTS)	f (Hz)	V_{OUT} (VOLTS)
100		6000	
200		7000	
300		8000	
400		9000	
500		10000	
600		20000	
700		30000	
800		40000	
900		50000	
1000		60000	
2000		70000	
3000		80000	
4000		90000	
5000		100000	

TABLE 2 - V_{OUT} versus frequency for the high pass filter.

14. Plot the results listed in Table 2 on the semi-log graph of Figure 10 and circle the curve at the half power point where it intersects the 2.1 volts (3 x 0.707).

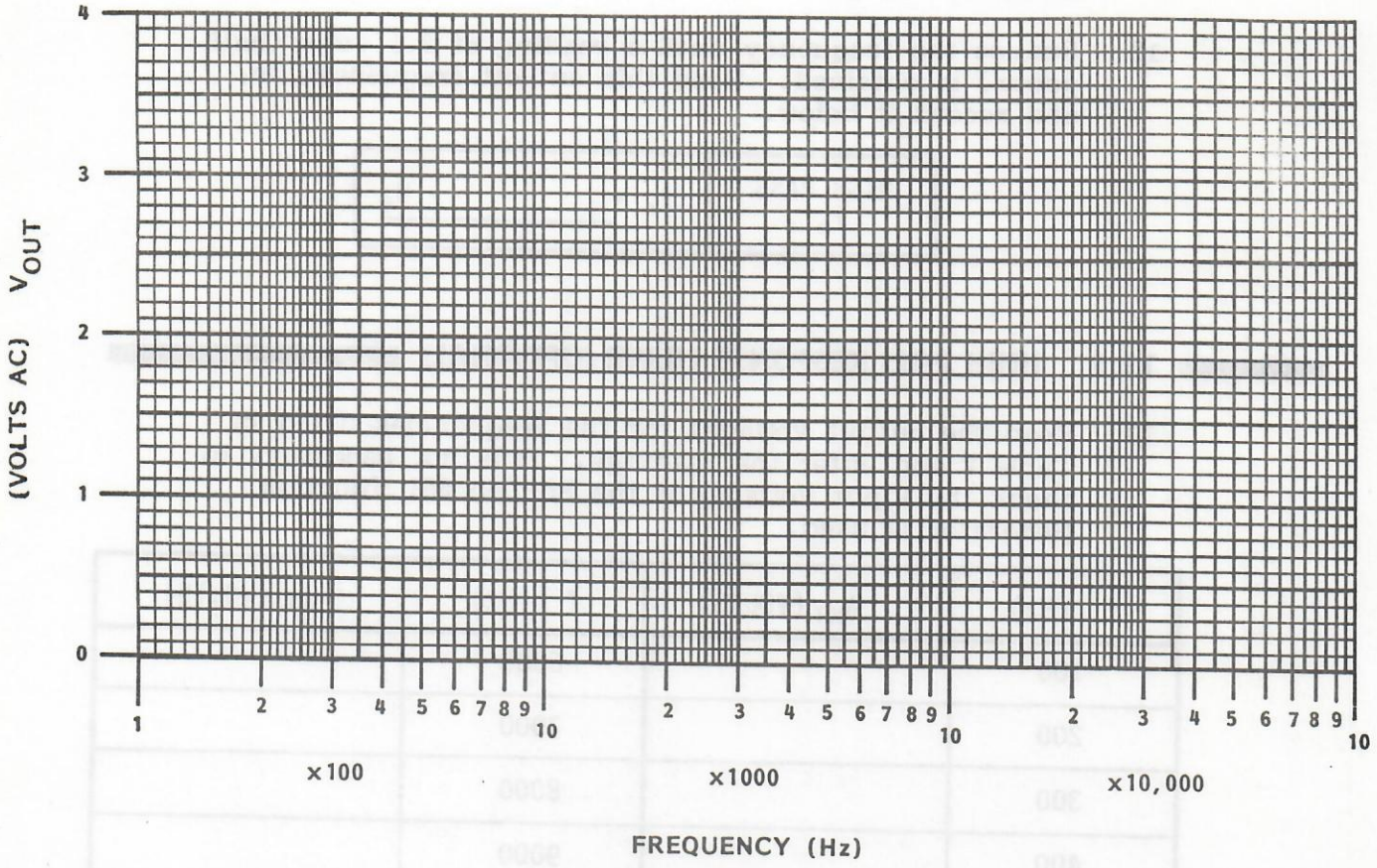


Figure 10 - Frequency response curve of the RL high pass filter.

The high pass RL filter cut-off frequency, f_c, should be very close to the low pass cut-off frequency found in steps 8 and 9.

CONCLUSIONS

We have learned from this experiment that:

The function of a filter circuit is to separate ac signals of different frequencies.

A filter circuit consists of a combination of R, L and C components.

A low pass filter passes low frequency signals and blocks the high frequency signals.

A high pass filter passes the high frequency signals and blocks the low frequency signals.

The voltage versus frequency characteristics of a filter is called the filter's Frequency Response.

The filter frequency response can be plotted on semi-log graph paper with frequency on the log axis (horizontal) and voltage on the linear axis.

The rejected frequencies are those that fall below the half power point.

The half power point is equal to 0.707 times the maximum voltage graphed in the response curve.

The frequency at which the half power point occurs is called the cut-off frequency and abbreviated f_c.

The cut-off frequency for an RL circuit is determined from:

$$f_c = \frac{R}{2\pi L}$$

Semi-log graphs can be obtained with 1, 2, 3 or 4 cycles on the log scale.

Log-log graphs are available in 2 x 2 cycles, 3 x 3 cycles or 4 x 4 cycles.

ASSIGNMENT

Answer the following multiple choice questions.

1. A low pass filter will _____ high frequencies and _____ low frequencies.

   a. pass; pass
   b. block; pass
   c. block; block
   d. pass; block

2. A high pass filter will _____ high frequencies and _____ low frequencies.

   a. pass; pass
   b. block; pass
   c. block; block
   d. pass; block

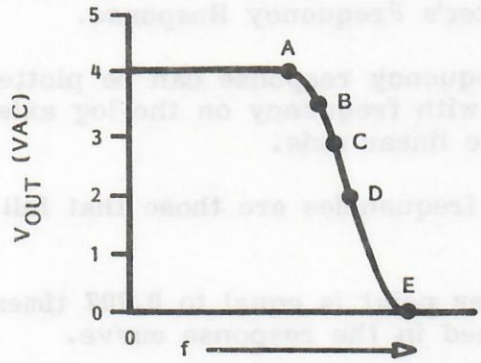


Figure 11, above, refers to questions 3 to 5.

3. Figure 11 is a response curve of a:

   a. low pass filter.
   b. high pass filter.
   c. band pass filter.
   d. band stop filter.

4. The rejected frequencies indicated by the response curve in Figure 11 are:

   a. to the left of point A.
   b. to the right of point A.
   c. to the left of point B.
   d. to the right of point C.

5. The half power point in the response curve of Figure 11 is located on the curve at point:

   a. B.
   c. C.
   c. D.
   d. E.

6. The cut-off frequency of an RL filter is:

   a. found from $f_c = \dfrac{1}{2\pi\sqrt{LR}}$
   b. determined by $f_c = RL/2\pi$
   c. calculated from $f_c = R/2\pi L$
   d. determined from any one of the above equations.

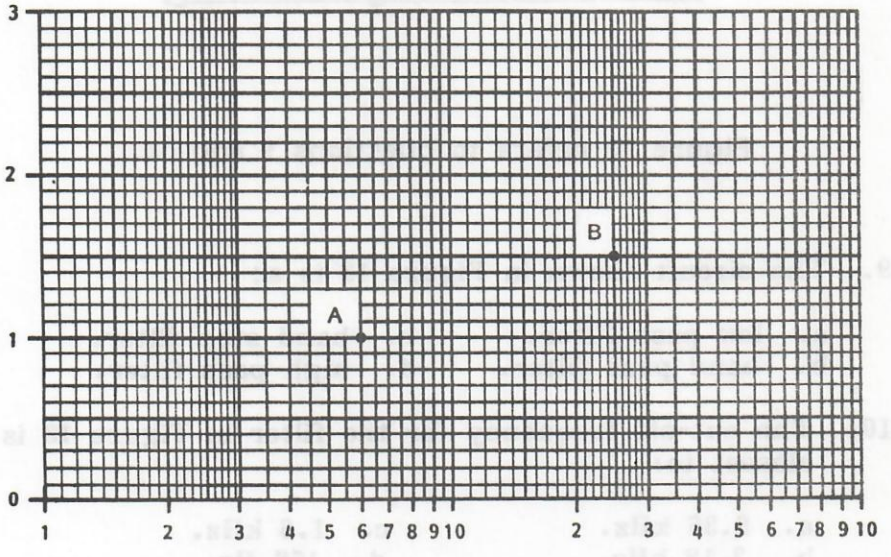


Figure 12 refers to questions 7 and 8.

7. The graph shown in Figure 12 is:

   a. rectilinear.
   b. log-log 2 cycle.
   c. semi-log.
   d. linear

8. On the graph of Figure 12, the X axis is calibrated in frequency and the first cycle is in Hz x 10. The frequency represented by A is _____ Hz and by B is _____ Hz.

   a. 60; 250
   b. 90; 400
   c. 45; 300
   d. 450; 3000

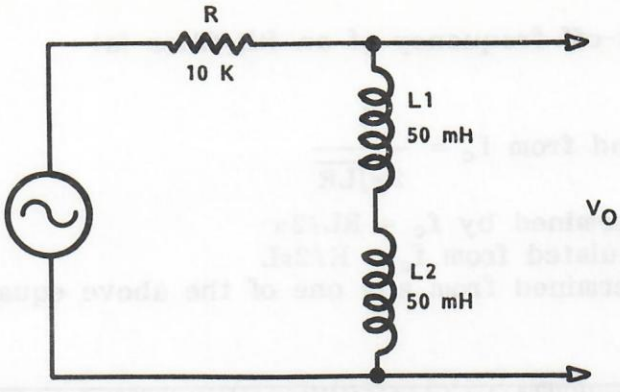


Figure 13 refers to questions 9 and 10.

9. The circuit shown in Figure 13 is a:

   a. low pass filter.
   b. band pass filter.
   c. band stop filter.
   d. high pass filter.

10. The cut-off frequency for the filter in Figure 13 is closest to:

   a. 6.36 kHz.
   b. 3.18 kHz.
   c. 1.6 kHz.
   d. 159 Hz.

KEY TERMS

1. CORNER FREQUENCY (f_c)

   Also known as the "Cut-Off" frequency. It is the frequency at which the output signal drops to half power or 70.7% of the maximum voltage.

2. CUT OFF FREQUENCY (f_c)

   See 1 above, Corner Frequency.

3. FILTER CIRCUIT

   A circuit consisting of R, L and C components wired so that one range of frequencies appear at the output while all other frequencies are blocked.

4. HIGH PASS FILTER

   A filter circuit that blocks all low frequencies below the cut off frequency, f_c, and passes all frequencies above f_c.

5. LOGARITHMIC GRAPH

   A graph with at least one of the axis calibrated logarithimically instead of linearly.

6. LOG-LOG GRAPH

   A graph in which both the X and Y axis are calibrated logarithimically.

7. LOW PASS FILTER

   A filter circuit that blocks all high frequencies above the cut-off frequency, f_c, and passes all frequencies below f_c.

8. RL FILTER

   A filter circuit formed with resistors and inductors.

9. SEMI-LOG GRAPH

   A graph with one axis calibrated logarithimically and the second axis calibrated linearly.

RC Filter Circuits

12

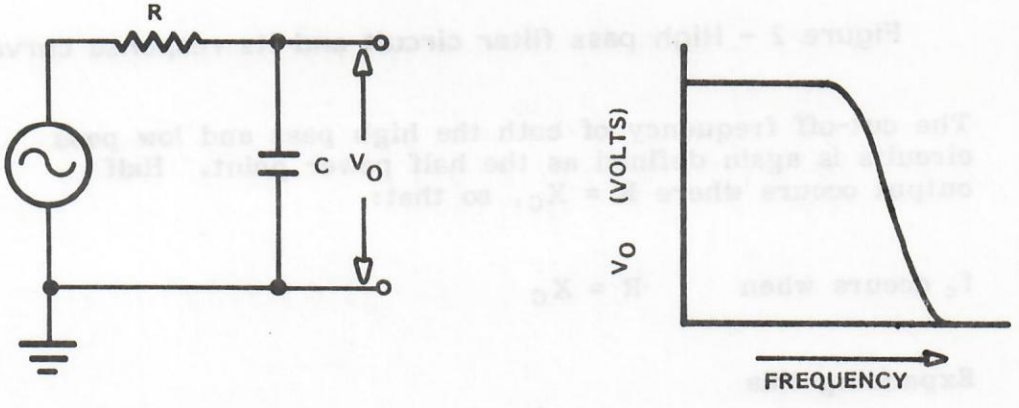
OBJECTIVES

When you finish this experiment you will be able to:

1. Explain the operation of an RC low pass filter.
2. Explain the operation of an RC high pass filter.
3. Wire and test the operation of RC high pass and low pass filters.
4. Plot the frequency response curves of RC filters on semi-log graph paper.
5. Measure and calculate the cut-off frequency of an RC filter.

DESCRIPTION

The RC high pass and low pass filters operate in the same manner as the RL filters described earlier in Experiment 11. The substitution of a capacitive reactance for the inductive reactance causes a change in the filter configurations. As shown in Figure 1, the output for the LOW PASS FILTER is taken across the capacitor.



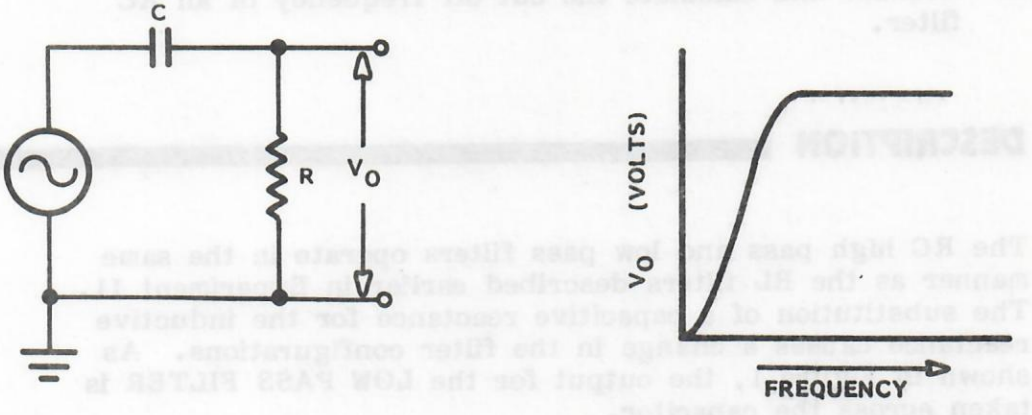
(a) LOW PASS RC FILTER

(b) LOW PASS FILTER RESPONSE

Figure 1 - Low pass filter and its response curve.

At low frequencies, X_C is very high compared to R and therefore most of the input signal or voltage appears across C and very little is "dropped" across R. The output is high and the circuit "passes" the input. As the input frequency increases, X_C drops and the output voltage, V_O, across C, drops. At high frequencies, the input signal does not "pass" but is "stopped."

The RC HIGH PASS FILTER circuit is shown in Figure 2 with its response curve. As shown, the output is taken across R and at low frequencies, with X_C very high, the output is low. As the input frequency is increased, X_C drops in comparison to R, and more of the input voltage appears across R.



(a) HIGH PASS RC FILTER.

(b) HIGH PASS FILTER RESPONSE

Figure 2 - High pass filter circuit and its response curve.

The cut-off frequency of both the high pass and low pass circuits is again defined as the half power point. Half output occurs where $R = X_C$, so that:

f_c occurs when $R = X_C$

Expanding this

$$R = \frac{1}{2\pi f_c C}$$

Transposing

RC FILTER CUT-OFF FREQUENCY HIGH PASS AND LOW PASS	$f_c = \frac{1}{2\pi RC}$

BANDPASS FILTER

It is possible to combine a low and high pass filter circuit to create a BAND PASS FILTER. The combined response curves are shown in Figure 3.

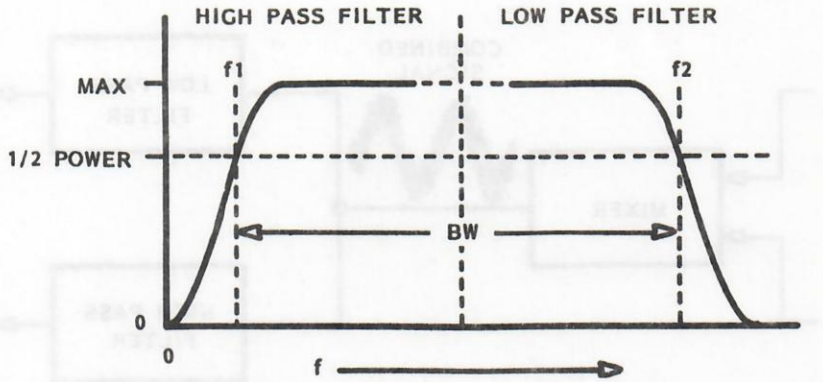


Figure 3 - Band pass response when high and low pass filters are combined.

The low frequency cut-off, f_1, is set by the half power point of the high pass filter and the high frequency half power point cut-off, f_2, is set by the low pass filter. A combined filter circuit and a variation of that circuit is shown in Figure 4.

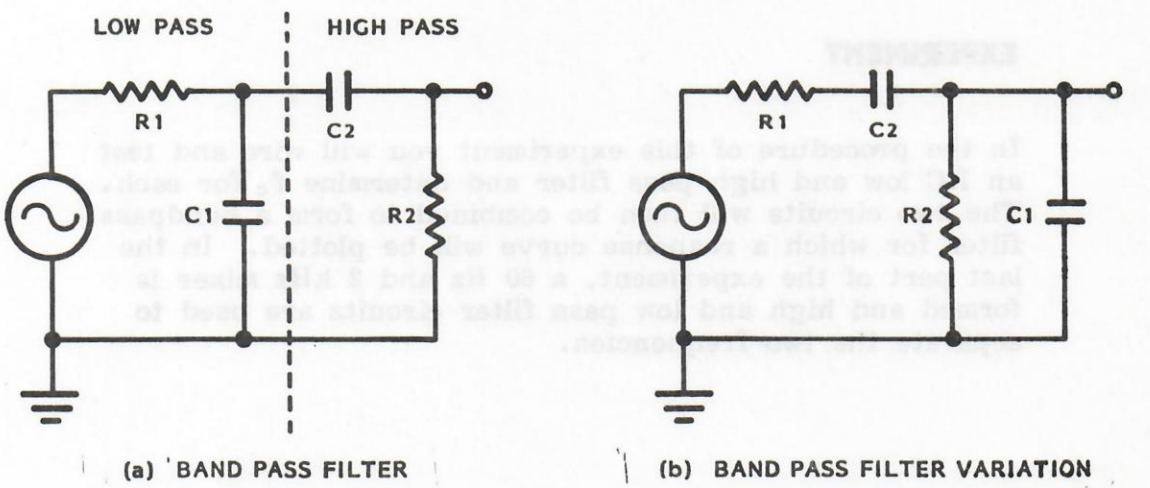


Figure 4 - Combined low and high pass filter circuits.

FREQUENCY SEPARATION

When frequencies are combined or "mixed" into a single composite signal, they can be separated by the use of low and high pass filters. This is shown in block diagram form in Figure 5.

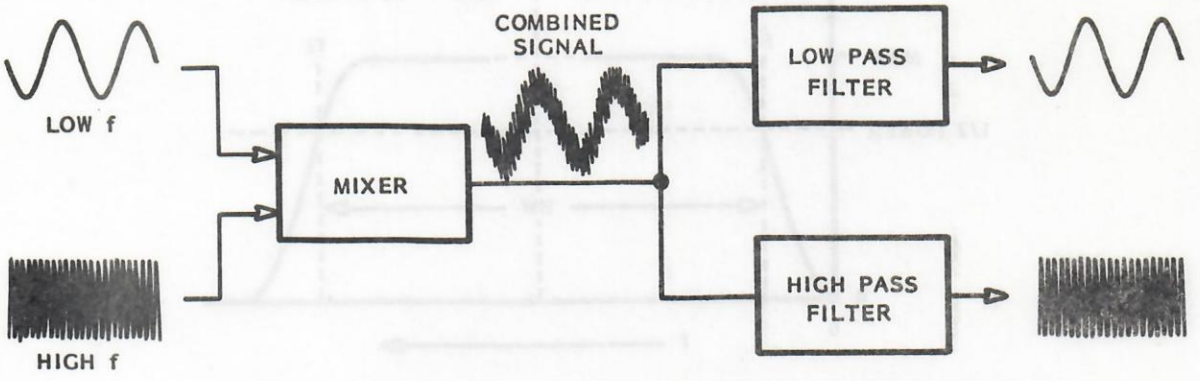


Figure 5 - Filters used to separate signals of different frequencies.

Filter systems such as shown in Figure 5 are used in television systems for the separation of 60 Hz and 15,750 Hz synchronization signals and in high fidelity systems for the separation of high and low audio frequency signals fed to the woofers and tweeters.

EXPERIMENT

In the procedure of this experiment you will wire and test an RC low and high pass filter and determine f_c for each. The two circuits will then be combined to form a bandpass filter for which a response curve will be plotted. In the last part of the experiment, a 60 Hz and 2 kHz mixer is formed and high and low pass filter circuits are used to separate the two frequencies.

PROCEDURE

1. Wire the low pass RC filter shown in Figure 6.

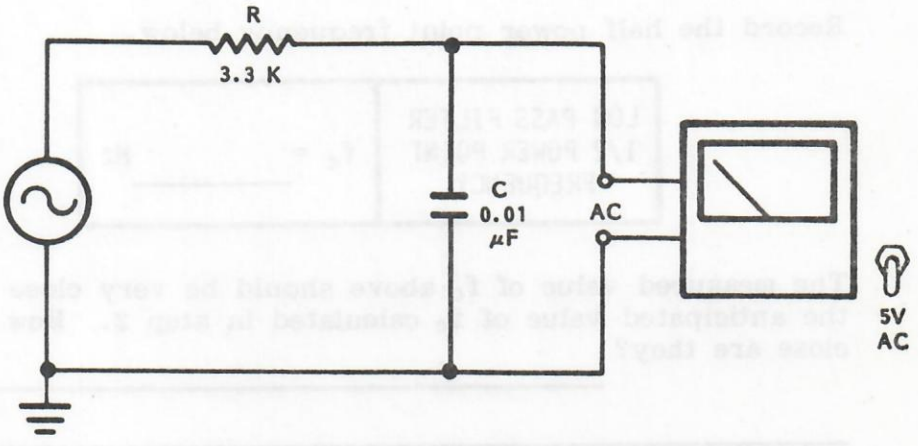


Figure 6 - Low pass RC filter EXPERIMENT.

Note that in Figure 6 above, switch A, as used in Experiment No. 11, Figure 7 which was needed to check the input voltage level, has been omitted. Check the input voltage only if an external signal source is used instead of the Ed-Lab Function Generator.

12.1 LOW PASS RC FILTER

2. The anticipated cut-off frequency for the low pass RC filter of Figure 6 with the component values shown is:

$$f_c = \frac{1}{2\pi RC}$$

$$= \frac{1}{(6.28)(3.3 \times 10^3)(0.01 \times 10^{-6})} = \frac{1{,}000}{0.20724}$$

THEORETICAL CUT-OFF FREQUENCY	f_c = 4,825 Hz

3. Set the Function Generator to 500 Hz, a low frequency which "passes," and adjust the Function Generator level control for a 3 volt output.

4. Increase the frequency until the output voltage drops from 3 volts to 2.1 volts, the half power point (0.707 X 3).

   Record the half power point frequency below.

LOW PASS FILTER 1/2 POWER POINT FREQUENCY	f_c = _____ Hz

   The measured value of f_c above should be very close to the anticipated value of f_c calculated in step 2. How close are they?

   _____

   _____

5. Set the Function Generator to each frequency listed in Table 1 and record the output voltages. Do not change the input signal level.

f (Hz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
200		4	
300		5	
400		6	
500		7	
600		8	
700		9	
800		10	
900		20	
1000		20	
2000		40	
3000		50	

TABLE 1 - V_{OUT} versus frequency for the RC low pass filter.

6. Plot the results of Table 1 on the semi-log graph in Figure 7 and circle the point at which the curve crosses the half power point.

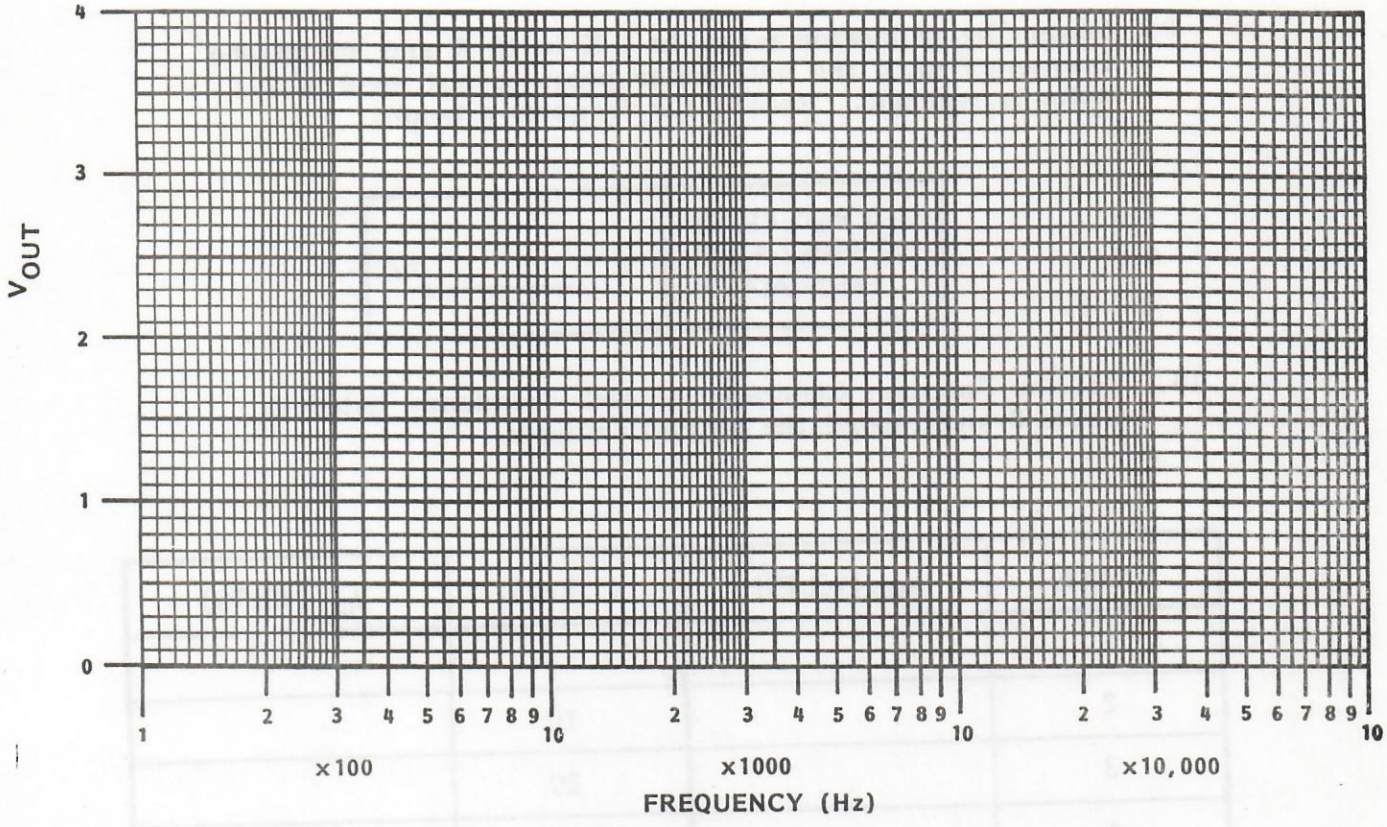


Figure 7 - Plot of V_{OUT} versus frequency for the low pass RC filter circuit.

12.2 HIGH PASS RC FILTER

7. Wire the high pass RC filter shown in Figure 8.

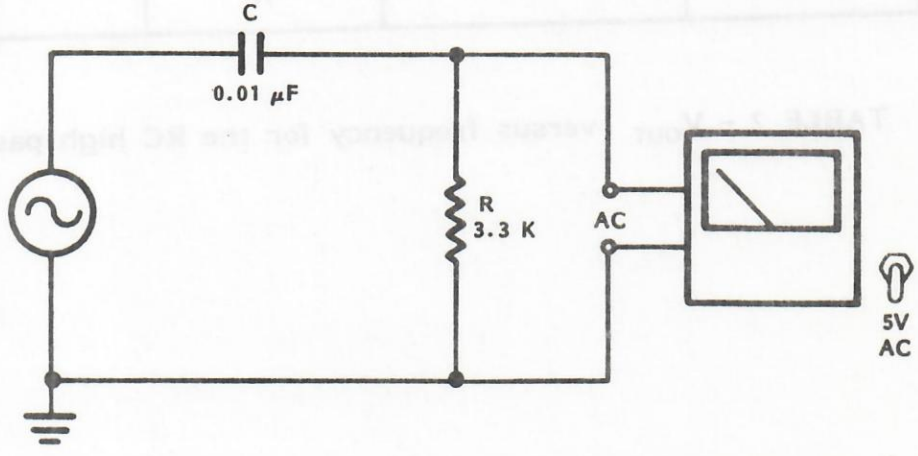


Figure 8 - High pass RC filter EXPERIMENT.

8. Set the Function Generator to 40 kHz, high above the cut-off frequency in the "pass" area, and adjust the output for 3 volts.

9. Lower the generator range to 1 K to 10 K and adjust the frequency until the half power point output level of 2.1 volts is reached. Record the frequency below.

HIGH PASS FILTER 1/2 POWER POINT FREQUENCY	f_c = _____ Hz

10. Set the Function Generator to each frequency listed in Table 2 and record the output voltages.

f (kHz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
1		9	
2		10	
3		20	
4		30	
5		40	
6		50	
7		60	
8		70	

TABLE 2 - V_{OUT} versus frequency for the RC high pass filter.

11. Plot the results of Table 2 on the semi-log graph in Figure 9 and circle the point at which the curve crosses the half power point.

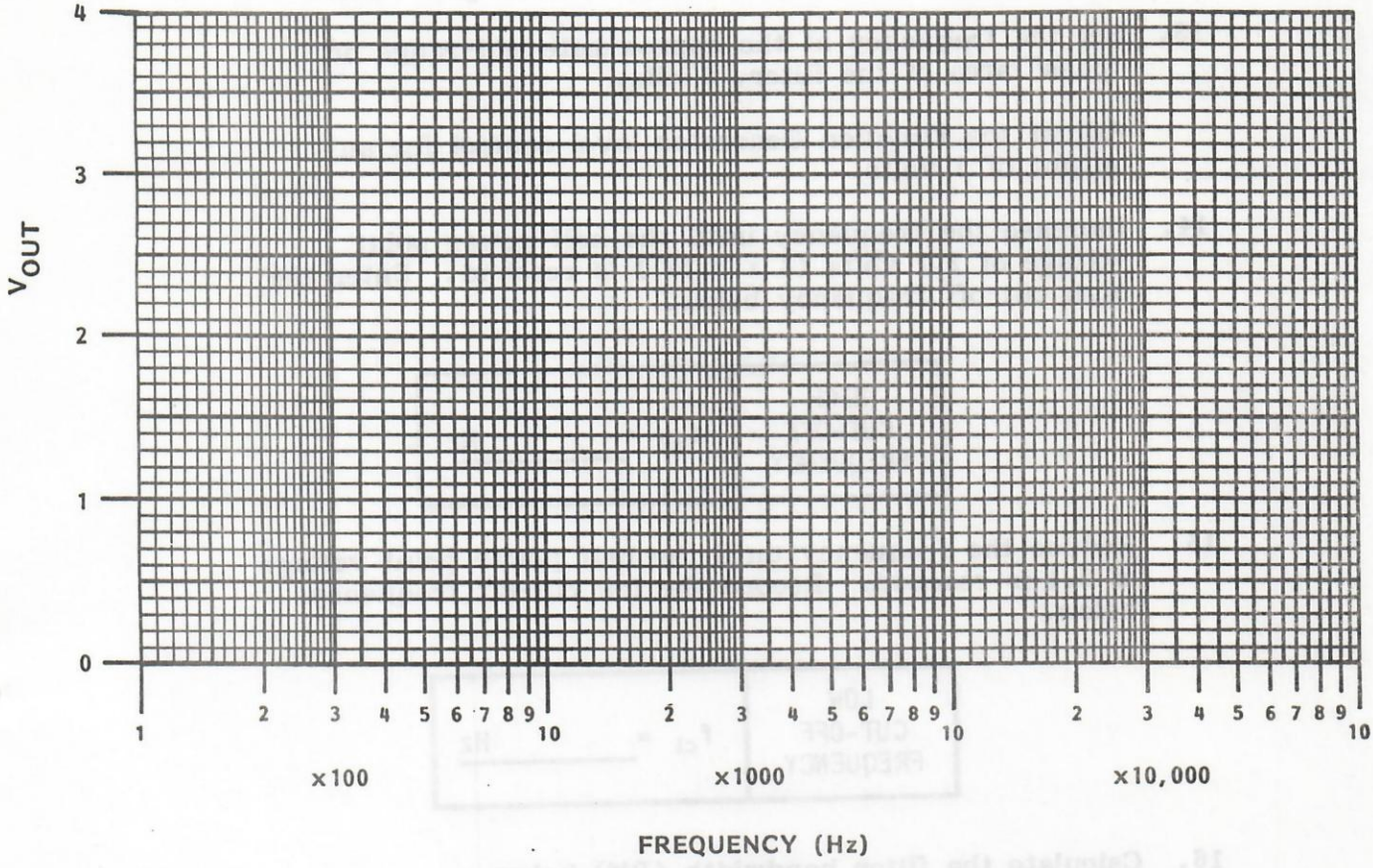


Figure 9 - Plot of V_{OUT} versus frequency for the high pass RC filter circuit.

12.3 BAND PASS RC FILTER

12. Remove all existing wiring and assemble the band pass filter shown in Figure 10.

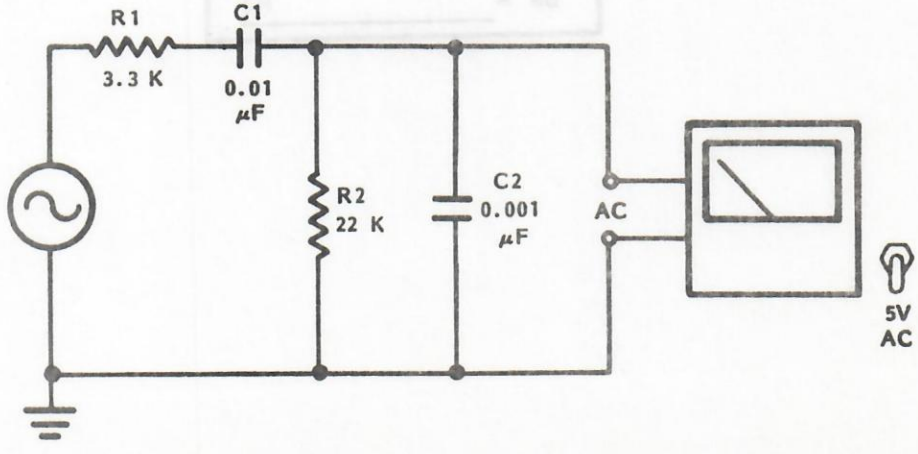


Figure 10 - Band pass RC filter EXPERIMENT.

At low frequencies, C_1 blocks the signals. At high frequencies C_2 "bypasses" or "loads" or "attenuates" the signals. The circuit is thus a band pass filter.

13. Set the frequency at the approximate mid-range or "pass" area of the filter, 5 kHz.

    Adjust the Function Generator level control for an output of 3 volts.

14. Increase the frequency until the half power point voltage of 2.1 volts (3 x 0.707) is reached. Enter the high cut-off frequency below.

HIGH CUT-OFF FREQUENCY	f_{c2} = _____ Hz

15. Reduce the frequency until the half power point voltage of 2.1 is reached. Record the low cut-off frequency below.

LOW CUT-OFF FREQUENCY	f_{c1} = _____ Hz

16. Calculate the filter bandwidth (BW) below.

$$BW = f_{c2} - f_{c1}$$

$$= (\quad) - (\quad)$$

BW = _____ Hz

17. Now measure the output voltage for each frequency listed in Table 2 and record the voltage readings.

f (Hz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
50		1	
60		2	
70		3	
80		4	
90		5	
100		10	
200		20	
300		30	
400		40	
500		50	
600		60	
700		70	
800		80	
900		90	

TABLE 3 - V_{OUT} versus frequency for the RC band pass filter.

18. Plot the band pass response data from Table 2 on the 4 cycle semi-log graph in Figure 11.

Observe that the 1/4 power level (0.707 x 1/2 power or 0.707 x 2.12), 1.5 volts, is also shown on this graph. This 1/4 power level is of interest in some applications as an indication of the "steepness" of the cut-off slope or "skirts."

The theoretical value of the center "resonant" frequency, f_r, of the band pass filter is given by the equation:

$$f_r = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

The resonant frequency, f_r, is then:

$$f_r = \frac{1}{6.28\sqrt{(3.3 \times 10^3)(0.01 \times 10^{-6})(22 \times 10^3)(0.001 \times 10^{-6})}}$$

$$= \frac{1}{6.28\sqrt{726 \times 10^{-12}}} = \frac{10^6}{169}$$

$$f_r = 5917 \text{ Hz}$$

Show this point by an arrow on the curve plotted in Figure 11.

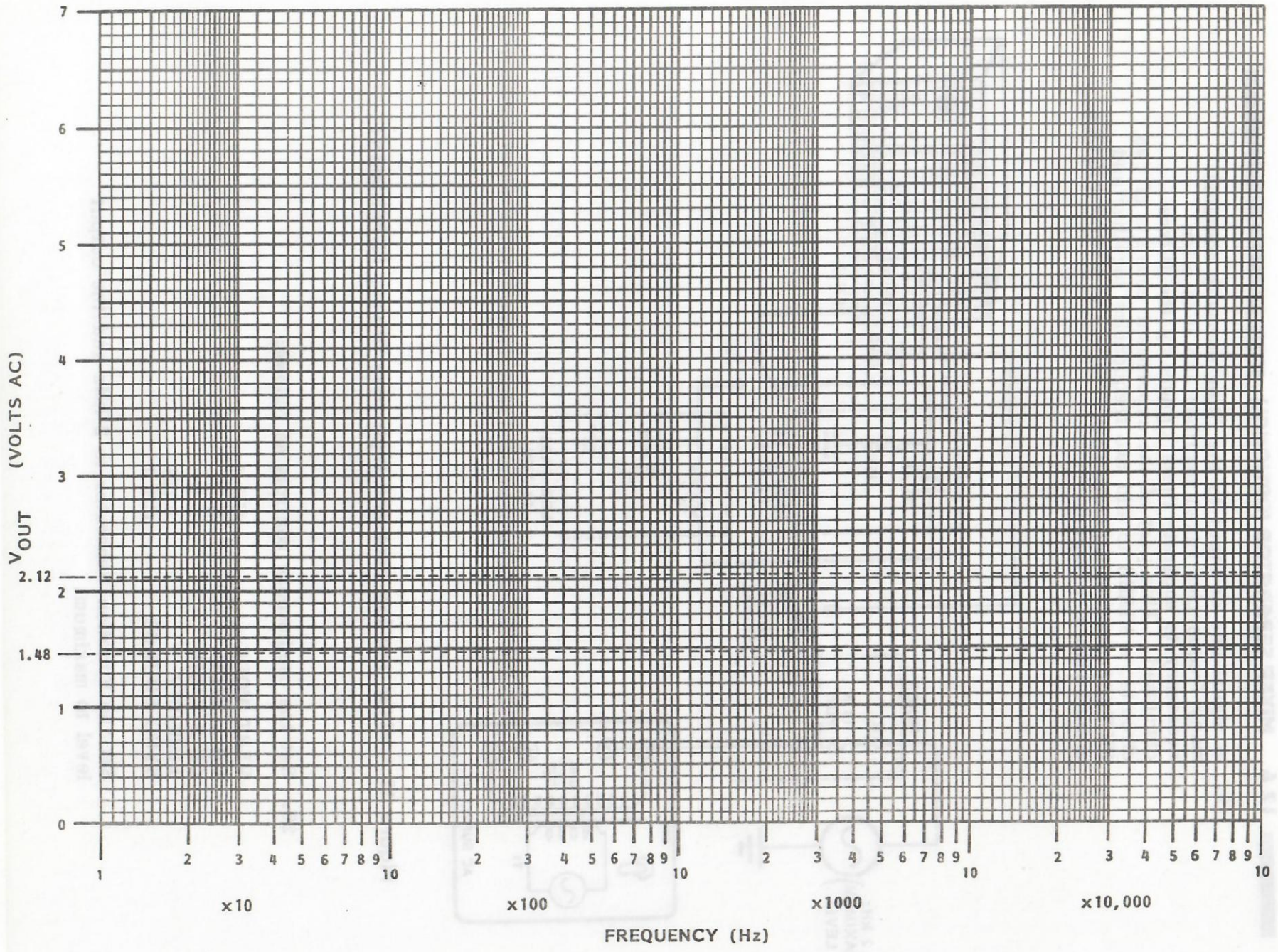


Figure 11 - Plot of V_{OUT} versus frequency for the RC band pass filter circuit.

12.4 MIXER SEPARATOR (OPTIONAL)

19. A signal line or input to the filter normally contains many frequencies mixed together and it is often necessary to separate these signals by the filters discussed. This part of the experiment consists of two circuits, a MIXER to add two frequencies together and FILTERS used to separate them. Wire the MIXER-FILTER circuit shown in Figure 12.

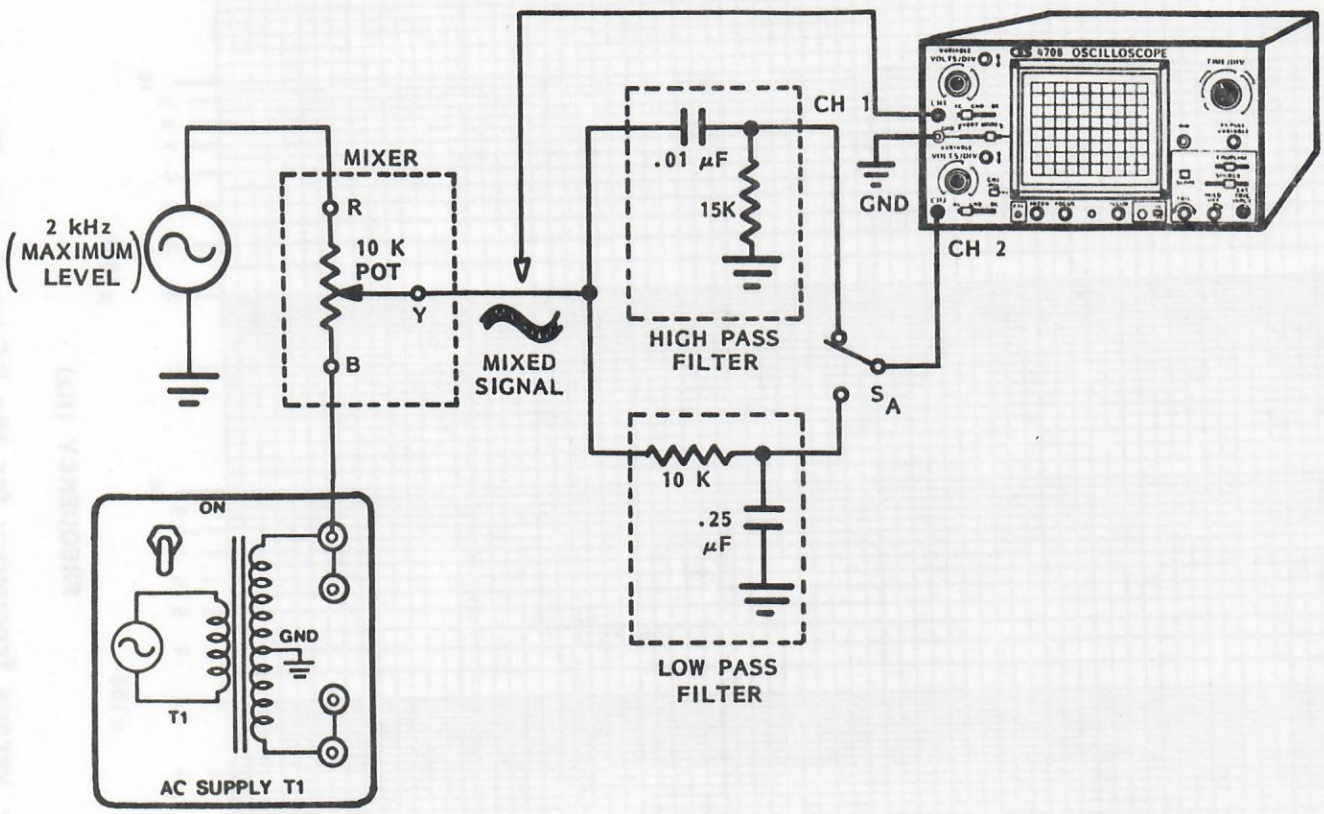


Figure 12 - Mixer and low pass and high pass filters; EXPERIMENT.

20. Set the oscilloscope controls as follows:

VERT MODE	CH 1
CH 1 V/DIV	5 V
CH 2 V/DIV	5 V
TIME/DIV	2 mS
SYNC SOURCE	CH 1

Set the Function Generator to 2 kHz and the output level to maximum.

21. Observe the CH 1 display and vary the 10 K pot. You will notice that at the CCW rotation position of the potentiometer, the 60 Hz signal is maximum and at CW rotation the 2 kHz signal is at maximum and only the 2 kHz signal is observed.

    Adjust the 10 K pot until both the 60 Hz and 2 kHz signals are equal, as shown in Figure 13. They will be approximately 1.5 cm peak-to-peak each.

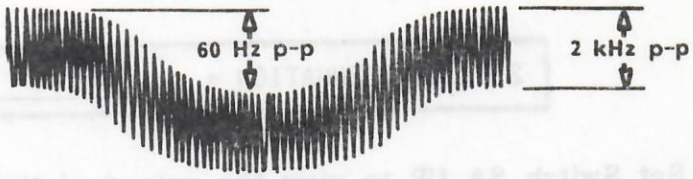
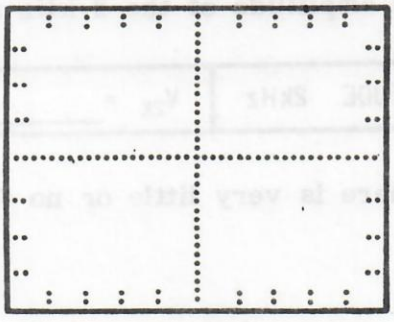


Figure 13 - Output waveform of the mixer circuit.

22. Set the oscilloscope to CHOP to display both channels. Center CH 1 (mixed frequencies) at the top of the screen and CH 2 (filtered signal) at the bottom.

23. Set the Switch SA DOWN to view the output of the LOW PASS FILTER. Sketch the filter output waveform below.



24. Measure the amplitude of the 60 Hz waveform and measure the small level of the 2 kHz signal "riding" on the 60 Hz signal.

AMPLITUDE 2 kHz	V_{2K} = _____ Vp-p
AMPLITUDE 60 Hz	V_{60} = _____ Vp-p

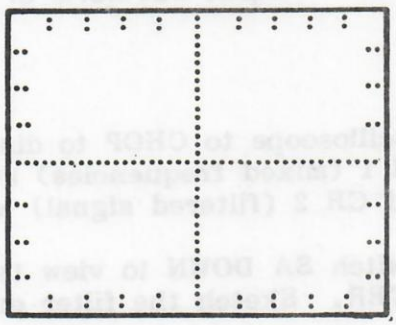
Calculate the decreases or ATTENUATION of the 2 kHz signal caused by the low pass filter.

$$\text{ATTENUATION} = \frac{V_{2K}}{V_{60\ Hz}}$$

$$= \frac{(\qquad)}{(\qquad)}$$

2 kHz ATTENUATION = _____

25. Set Switch SA UP to view the output of the HIGH PASS FILTER. Sketch the filter output waveform below.



26. Measure the amplitude of the 2 kHz signal.

AMPLITUDE 2kHz	V_{2K} = _____ Vp-p

Note that there is very little or no 60 Hz signal present.

CONCLUSIONS

We have learned from this experiment that:

In a low pass RC filter, the output is taken from across C.

In a high pass RC filter, the output is taken from across R.

The cut-off frequency occurs when V_{OUT} drops to 0.707 times $V_{OUT\ maximum}$.

The cut-off frequency can be calculated from:

$$f_c = \frac{1}{2\pi RC}$$

An RC band pass filter is a combination of a low and high pass filter.

Combined or mixed high and low frequency signals can be separated using a high and low pass filter combination.

The frequency response of an RC high and low pass filter is plotted on semi-log graph paper.

Four cycle semi-log graph paper can be used to cover from 10 Hz to 100 kHz, the first cycle covering x 10, the second x 100, the third x 1,000 and the fourth cycle, x 10,000.

ASSIGNMENT

Answer the following multiple choice questions.

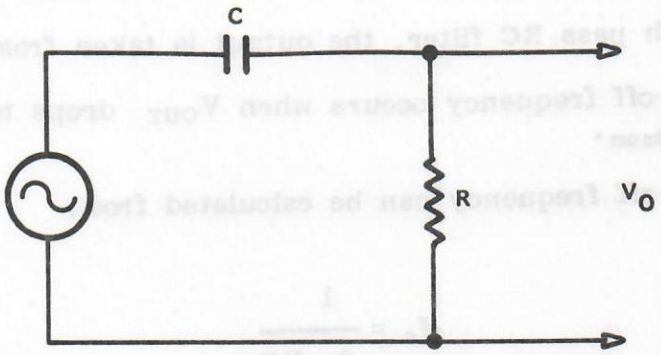


Figure 14 refers to questions 1 to 4.

1. The circuit of Figure 14 is a (an):

   a. RL high pass filter.
   b. RC low pass filter.
   c. RC high pass filter.
   d. band pass filter.

2. As the input frequency to the circuit of Figure 14 decreases, X_C _____ and V_O _____.

   a. increases; decreases.
   b. decreases; increases.
   c. increases; increases.
   d. decreases; decreases.

3. For the circuit of Figure 14, given an R of 40 K and a C of 0.22 μF, f_c is closest to:

   a. 294 Hz.
   b. 122 Hz.
   c. 55 Hz.
   d. 18 Hz.

4. When the input frequency in Figure 14 is at the f_c value:

   a. $X_C = 2R$.
   b. $2X_C = 2R$.
   c. $2X_C = R/2$.
   d. $V_O = 2.12 \times V_{MAX}$.

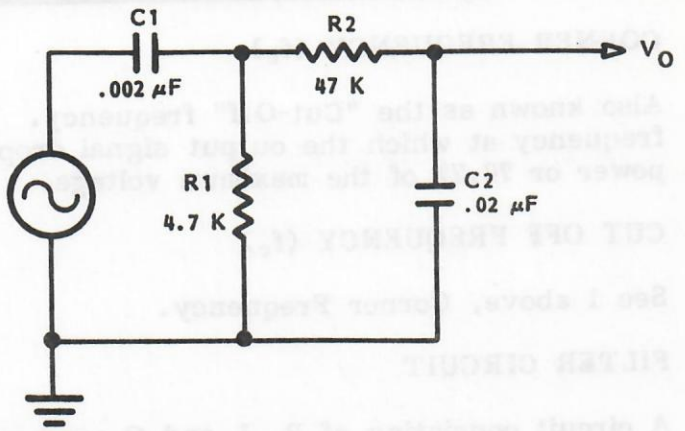


Figure 15 refers to questions 5 to 10.

5. The circuit of Figure 15 is closest to a:

   a. low pass filter.
   b. high pass filter.
   c. band stop filter.
   d. band pass filter.

6. In the circuit of Figure 15, a low pass filter is formed by:

   a. C1 and C2.
   b. R1 and R2.
   c. R1 and C1.
   d. C2 and R2.

7. In the circuit of Figure 15, a high pass filter is formed by:

   a. C1 and C2.
   b. R1 and R2.
   c. R1 and C1.
   d. C2 and R2.

8. The f_1 point for Figure 15 is closest to:

   a. 169 Hz.
   b. 1,694 Hz.
   c. 16,940 Hz.
   d. there is no f_1 for this circuit.

9. The f_2 point for Figure 15 is closest to:

   a. 169 Hz.
   b. 1694 Hz.
   c. 16,940 Hz.
   d. there is no f_2 for this circuit.

10. The bandwidth for the circuit in Figure 15 is closest to:

    a. 17,609 Hz.
    b. 16,771 Hz.
    c. 285,610 ohms.
    d. none of the above.

KEY TERMS

1. CORNER FREQUENCY (f_c)

   Also known as the "Cut-Off" frequency. It is the frequency at which the output signal drops to half power or 70.7% of the maximum voltage.

2. CUT OFF FREQUENCY (f_c)

   See 1 above, Corner Frequency.

3. FILTER CIRCUIT

   A circuit consisting of R, L and C components wired so that one range of frequencies appear at the output while all other frequencies are blocked.

4. HIGH PASS FILTER

   A filter circuit that blocks all low frequencies below the cut off frequency, f_c, and passes all frequencies above f_c.

5. LOGARITHMIC GRAPH

   A graph with at least one of the axis calibrated logarithmically instead of linearly.

6. LOG-LOG GRAPH

   A graph in which both the X and Y axis are calibrated logarithimically.

7. LOW PASS FILTER

   A filter circuit that blocks all high frequencies above the cut-off frequency, f_c, and passes all frequencies below f_c.

8. RC FILTER

   A filter that contains resistors and capacitors.

9. SEMI-LOG GRAPH

   A graph with one axis calibrated logarithimically and the second axis calibrated linearly.

LC Filter Circuits 13

OBJECTIVES

When you finish this experiment you will be able to:

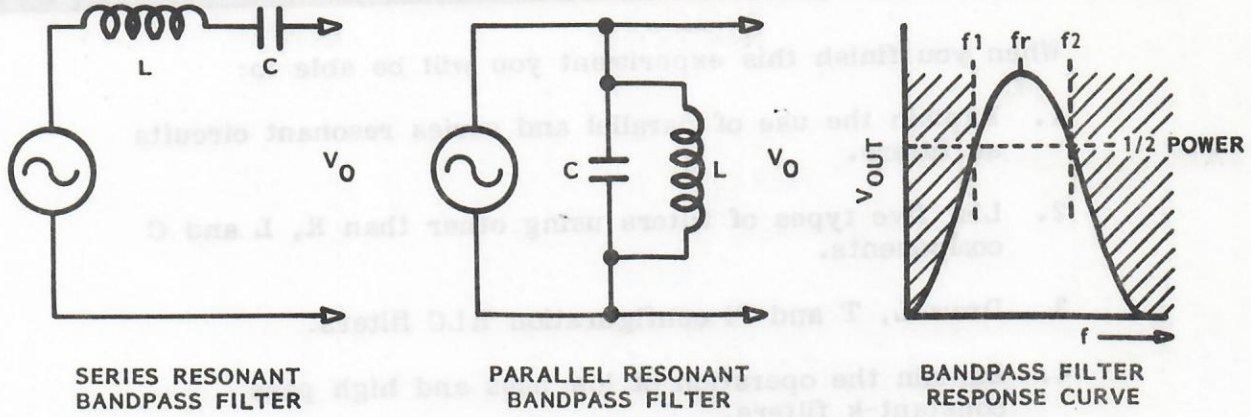
1. Explain the use of parallel and series resonant circuits as filters.
2. List five types of filters using other than R, L and C components.
3. Draw L, T and Pi configuration RLC filters.
4. Explain the operation of low pass and high pass constant-k filters.
5. Explain the operation of an m-derived filter.
6. Test and plot the characteristics of various LC filters.

DESCRIPTION

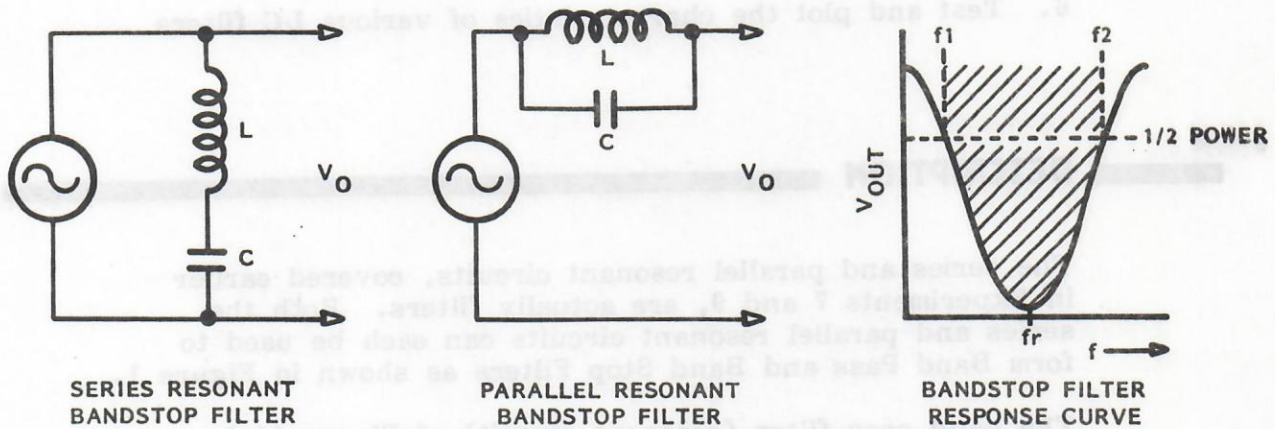
The series and parallel resonant circuits, covered earlier in Experiments 7 and 9, are actually filters. Both the series and parallel resonant circuits can each be used to form Band Pass and Band Stop Filters as shown in Figure 1.

The band pass filter (resonant circuit) of Figure 1(a) passes the narrow range of frequencies between f_1 and f_2. The band stop filter of Figure 1(b) passes all frequencies below f_1 and all frequencies above f_2 and stops all frequencies between f_1 and f_2.

In addition to the band pass and band stop filters shown in Figure 1, it is possible to arrange the L and C components so that they form "improved" low pass and high pass filters as well. LC low pass and high pass filters are very often favored over the RL and RC types because the output, after f_c is reached, drops off more sharply. This sharper drop in LC filters occurs because both filter elements, L and C, change reactance with frequency while in RL and RC filters, only the L or the C components change reactance.



(a) BANDPASS LC FILTERS AND RESPONSE CURVE



(b) BANDSTOP LC FILTERS AND RESPONSE CURVE

Figure 1 - Resonant LC filter circuits.

The study of filters is an advanced topic in electronic circuits. A variety of filter types are available in addition to those formed from R, L and C components. These other devices are:

a. Crystal Filters
b. Ceramic Filters
c. Digital Filters
d. Mechanical Filters
e. SAW (Surface Acoustical Wave) Filters
f. Active Filters

The LC type low pass filter configurations can appear as shown in Figure 2.

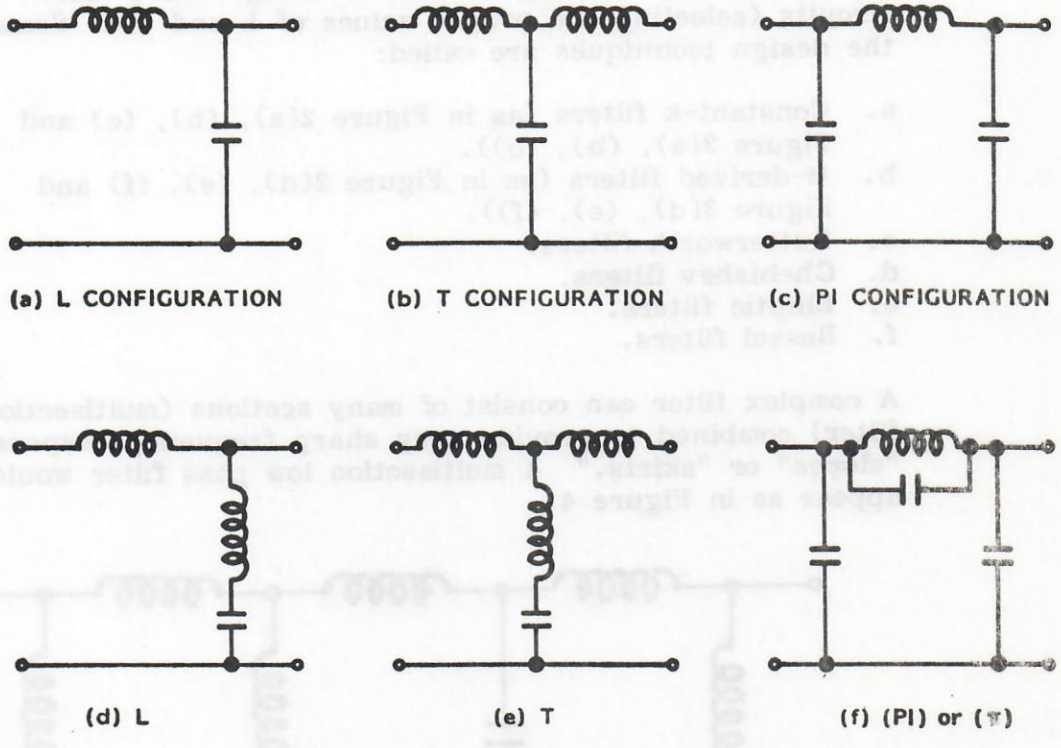


Figure 2 - Low pass filter circuits.

The LC type high pass filter configurations can appear as shown in Figure 3.

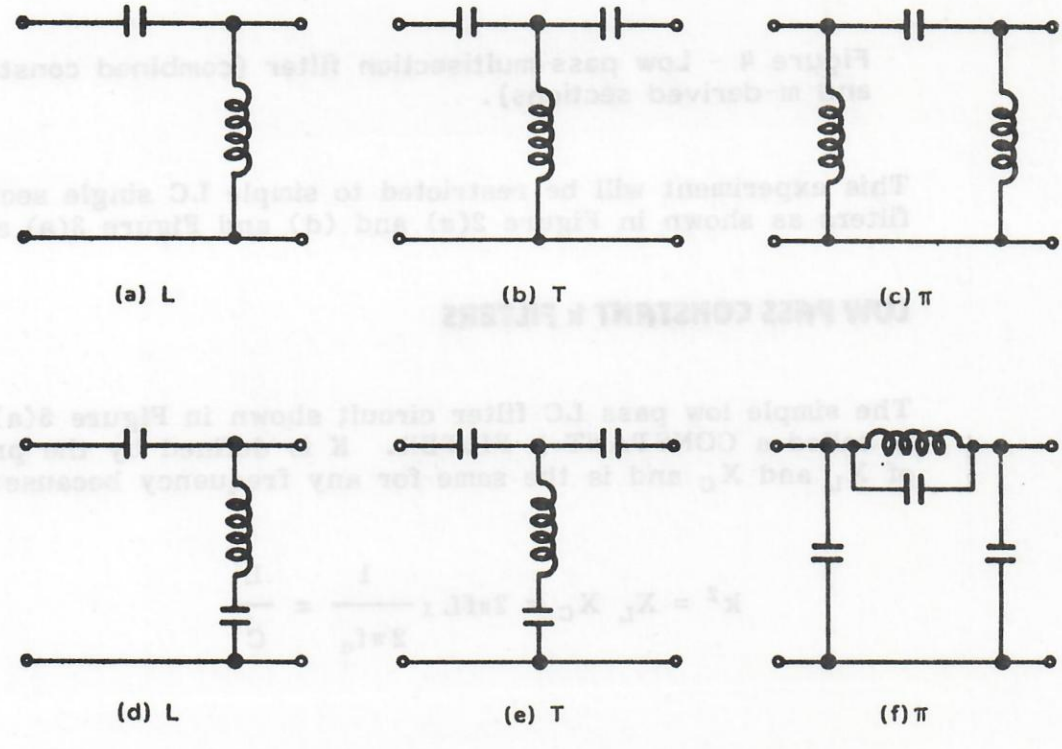


Figure 3 - High pass filter circuits.

4—LC FILTER CIRCUITS

There are many techniques used to design these filter circuits (selecting the proper values of L and C). Some of the design techniques are called:

a. Constant-k filters (as in Figure 2(a), (b), (c) and Figure 3(a), (b), (c)).
b. M-derived filters (as in Figure 2(d), (e), (f) and Figure 3(d), (e), (f)).
c. Butterworth filters.
d. Chebishev filters.
e. Elliptic filters.
f. Bessel filters.

A complex filter can consist of many sections (multisection filter) combined to provide very sharp frequency response, "slopes" or "skirts." A multisection low pass filter would appear as in Figure 4.

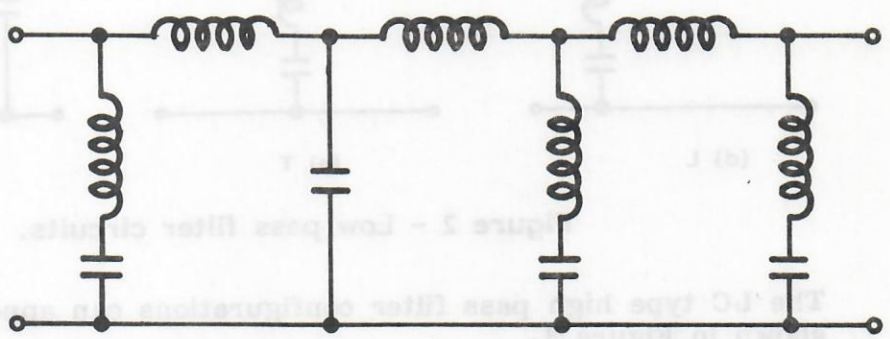


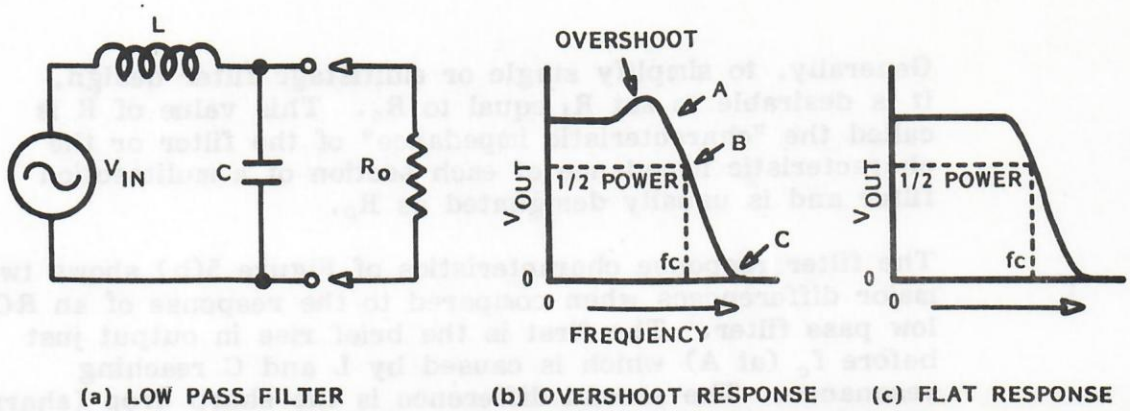
Figure 4 - Low pass multisection filter (combined constant-k and m-derived sections).

This experiment will be restricted to simple LC single section filters as shown in Figure 2(a) and (d) and Figure 3(a) and (d).

LOW PASS CONSTANT k FILTERS

The simple low pass LC filter circuit shown in Figure 5(a) is called a CONSTANT-k FILTER. K is defined by the product of X_L and X_C and is the same for any frequency because:

$$k^2 = X_L \, X_C = 2\pi f L \times \frac{1}{2\pi f_c} = \frac{L}{C} \qquad (1)$$

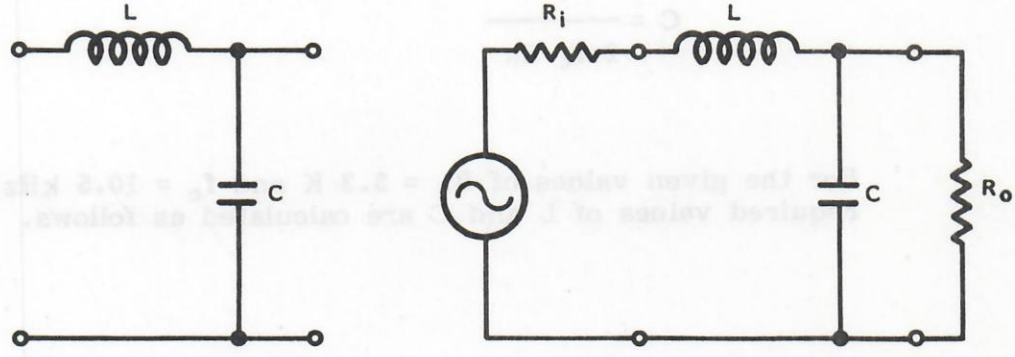


(a) LOW PASS FILTER (b) OVERSHOOT RESPONSE (c) FLAT RESPONSE

Figure 5 - Low pass constant k filter and response characteristics.

The basic operation of the low pass LC filter shown in Figure 5(a) is that, at low frequencies, X_L is low and easily passes signals through L. At the same time, for low frequencies, X_C is high and maximum voltage, V_o, appears across C. As the frequency rises, X_L increases and X_c decreases, both causing a reduction in V_o. The point at which V_o drops to 70.7% of maximum is the half power point or the cut-off frequency, f_c. Depending on the values of L, C and R_o, there may or may not be an overshoot (a resonant rise) as shown in Figure 5(b) and (c).

When designing any filter, it is necessary to consider the source impedance and the load impedance because they are part of the overall circuit. The simplified low pass LC filter is shown again in Figure 6(a) and the actual circuit, complete with input and output impedances, shown as resistances R_i and R_o, is shown in Figure 6(b).



(a) BASIC LC FILTER (b) ACTUAL LC FILTER CIRCUIT

Figure 6 - Simplified and actual LC filter circuit.

Generally, to simplify single or multistage filter design, it is desirable to set R_i equal to R_o. This value of R is called the "characteristic impedance" of the filter or the characteristic impedance of each section of a mulitsection filter and is usually designated as R_o.

The filter response characteristics of Figure 5(b) shows two major differencecs when compared to the response of an RC low pass filter. The first is the brief rise in output just before f_c (at A) which is caused by L and C reaching resonance. The second difference is the sharp drop (sharp skirts) after resonance. This is also caused by the resonant state of L and C. The sharp drop on output from A to B to C resembles one half of the resonance curve. The higher the Q of the LC network, the sharper this drop will be.

Reference to various advanced texts covering filters show numerous equations and graphs that are used to design the filters to achieve the desired sharpness and cut-off frequency. One such set of typical equations for a constant-k filter is given below relating L, C, R_o and f_c.

The equation to determine L is:

$$L = \frac{R_o}{2\pi f_c} \qquad (2)$$

The equation to determine C is:

$$C = \frac{1}{2\pi f_c R_o} \qquad (3)$$

For the given values of R_o = 3.3 K and f_c = 10.5 kHz, the required values of L and C are calculated as follows.

$$L = \frac{R_o}{2\pi f_c}$$

$$= \frac{3.3 \times 10^3}{(6.28)(10.5 \times 10^3)}$$

$$\boxed{L = 0.05 \text{ H or } 50 \text{ mH}}$$

$$C = \frac{1}{2\pi f_c R_o}$$

$$= \frac{1}{(6.28)(10.5 \times 10^3)(3.3 \times 10^3)}$$

$$= \frac{10^{-6}}{(6.28)(10.5)(3.3)}$$

$$\boxed{C = 0.0046\ \mu F \cong 0.005\ \mu F}$$

The value of k in this constant-k filter is given by:

$$k^2 = \frac{L}{C}$$

$$\boxed{k = \sqrt{\frac{L}{C}}} \qquad (4)$$

$$= \sqrt{\frac{50 \times 10^{-3}}{0.005 \times 10^{-6}}}$$

$$\boxed{k = 3162}$$

and is constant for any frequency at which the filter is operated.

HIGH PASS CONSTANT k FILTERS

The HIGH PASS constant-k filter operates on the same basic principle as the low pass filter but the positions of L and C, in the circuit, are interchanged as shown in Figure 7(a). Now, at low frequencies X_C offers a very high reactance to block the input signal from the output, V_o. At the same time, at low frequencies, X_L is low and very little output is developed across the inductor; thus V_o is very low.

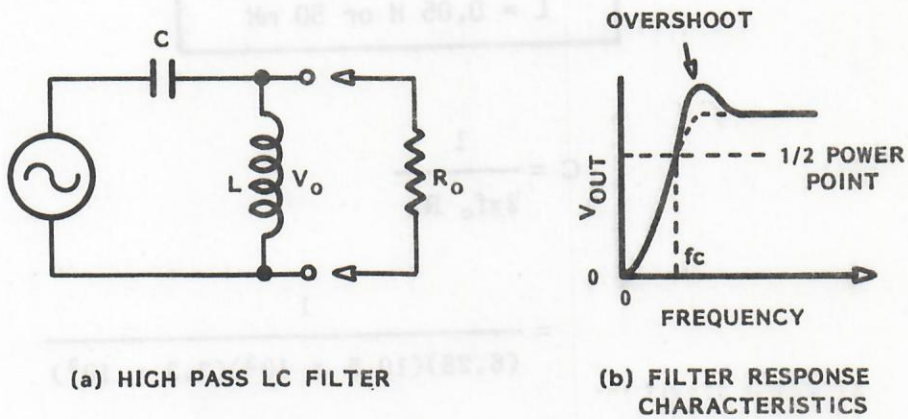


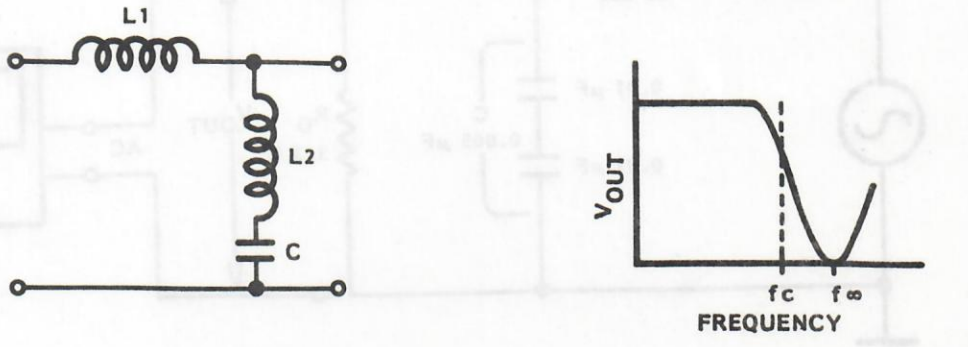
Figure 7 - Constant-k high pass LC filter circuit and frequency response characteristics.

As the input frequency in Figure 7(a) is increased, X_C drops and X_L rises to increase the output level. The output reaches the useable level at f_c, the half power point, and continues to increase with frequency. After the "overshoot", the output is equal to the generator input because X_C has dropped so low and X_L has risen so high.

The design equations for the high pass constant-k filter are the same as for the low pass filter (equations (2) and (3)) and will produce the same value of f_c for the same component values.

m-DERIVED FILTERS

The circuit of a low pass M-DERIVED filter is shown in Figure 8(a) and its response curve is shown in (b).



(a) LOW PASS M-DERIVED FILTER

(b) M-DERIVED FILTER RESPONSE

Figure 8 - Low pass m-derived filter and response.

Comparing the m-derived filter with the constant-k filter of Figure 5(a), it can be seen that the shunt arm contains a series combination of L_2 and C (series resonance.) The series network resonates at a frequency which theoretically corresponds to zero impedance and thus zero output. This frequency is marked $f\infty$ in Figure 8(b). ($f\infty$ refers to the frequency of infinite attenuation.)

The value of m is defined as a ratio between f_c (cut-off frequency) and $f\infty$ and, in normal filters, ranges from 0.5 to 1 with most practical filters operating in the range of 0.6. The equation is:

$$m^2 = 1 - \left(\frac{f_c}{f\infty}\right)^2$$

$$\boxed{m = \sqrt{1 - \left(\frac{f_c}{f\infty}\right)^2}} \qquad (5)$$

The advantages of the m-derived filter compared to the constant-k filter is that the m-derived filter has a sharper roll-off or attenuation after the cut-off frequency has been reached.

PROCEDURE

1. Wire the low pass LC constant-k filter circuit shown in Figure 9.

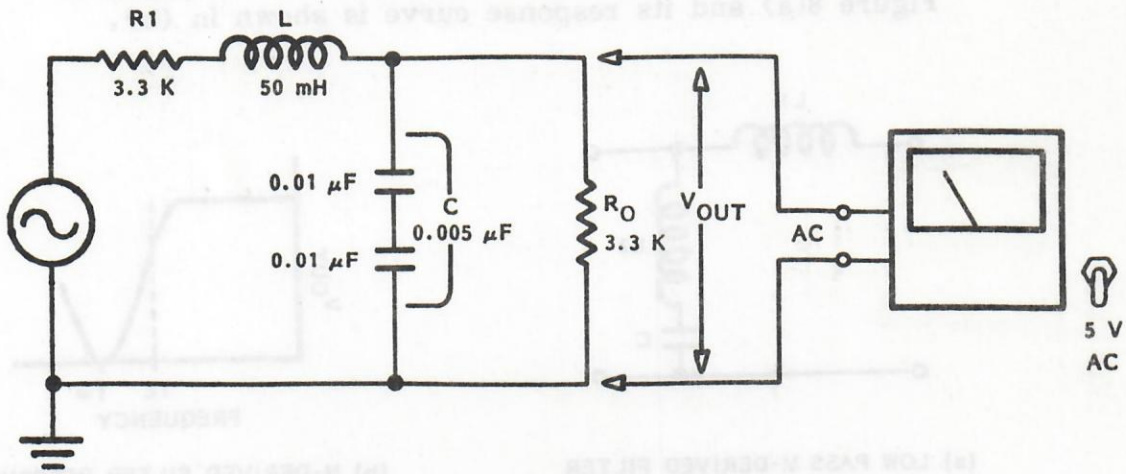


Figure 9 - Low pass constant-k filter circuit EXPERIMENT.

The 3.3 k resistor R_1, serves to set the input impedance, R_i, to equal the output impedance, R_o, also, 3.3 K.

The two 0.01 μF capacitors are wired in series to provide the required 0.005 μF for the desired cut-off frequency.

13.1 LOW PASS CONSTANT k LC FILTER

2. Set the Function Generator to a low frequency in the pass band, 500 Hz, and adjust the generator amplitude to result in a measured output level of 1.5 volts.

3. Calculate the voltage at which the cut-off frequency, f_c, will occur, as shown below.

$$V_o\ f_c = (V_{MAX})(0.707)$$

$$= (1.5)(0.707)$$

$V_o\ f_c =$ _____ V

4. Set the Function Generator range switch to 10 K - 100 K and adjust the frequency control for an output voltage as calculated in step 3 above. (It should be 1.06 volts.)

Record this measured cut-off frequency, f_c, below.

MEASURED CUT-OFF FREQUENCY	f_c = _____ kHz

5. Set the Function Generator to each of the frequencies listed in Table 1, read the output voltages and record them.

f (Hz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
200	1.5	7	
300		8	
500		9	
700		10	
900		15	
2000		20	
3000		25	
4000		30	
5000		40	
6000		50	

TABLE 1 - V_{OUT} versus frequency for the low pass constant-k LC filter.

13.2 FREQUENCY RESPONSE CURVE

6. Plot the resuts in Table 1 on the three cycle semi-log graph in Figure 10.

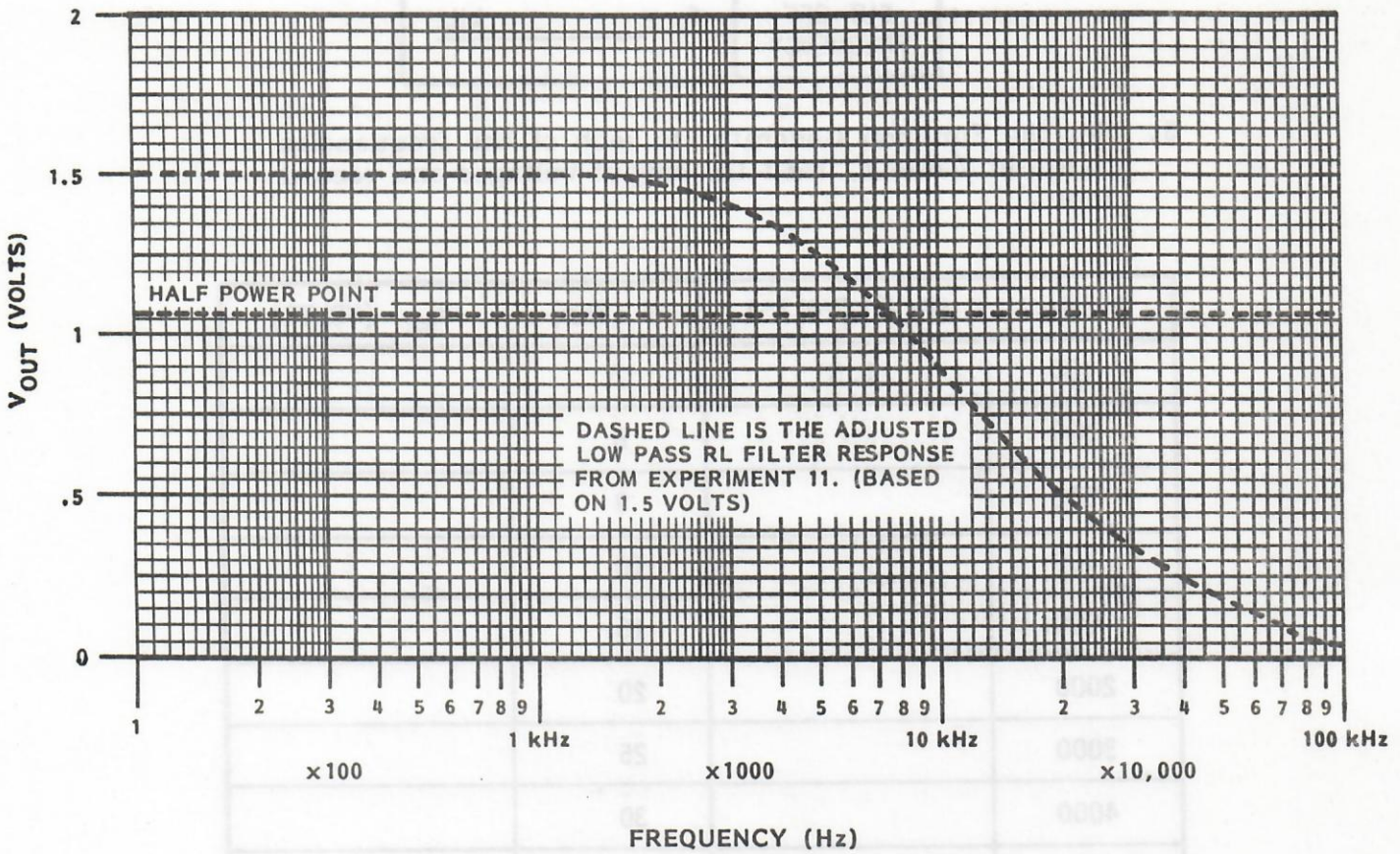


Figure 10 - Graph for plotting V_{OUT} versus frequency for the low pass LC filter; EXPERIMENT.

7. Examination of the results of the plot of Figure 10 shows that the roll-off or slope following the cut-off frequency for the LC filter is much steeper than that of the RL filter (shown by the dashed line) from an earlier experiment.

   What do you observe when comparing the roll-off characteristics of the two response curves plotted in Figure 10?

   _____

   _____

   _____

   _____

13.3 HIGH PASS CONSTANT k FILTER

8. Remove the existing wiring from the trainer panel and assemble the circuit shown in Figure 11.

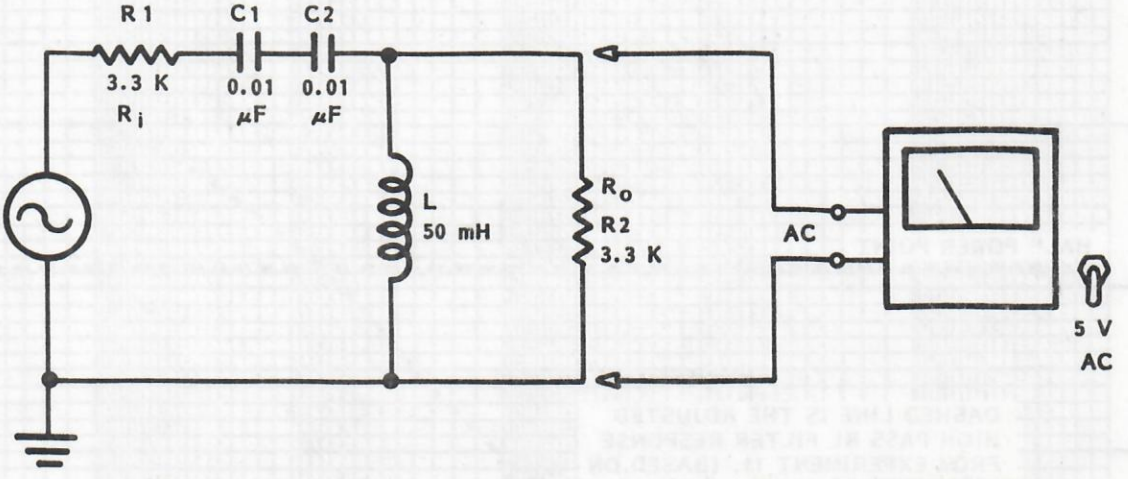


Figure 11 - High pass LC constant-k filter EXPERIMENT.

9. Set the Function Generator to a high pass frequency of 50 kHz and adjust the output level to 1.5 volts.

10. Set the Function Generator to each of the frequencies listed in Table 2, read the output voltages and record them.

f (kHz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
1		14	
2		15	
3		20	
4		25	
5		30	
6		40	
7		50	
8		60	
9		70	
10		80	
12		100	

TABLE 2 - V_{OUT} versus frequency for the high pass constant-k LC filter.

11. Plot the results listed in Table 2 on the three cycle semi-log graph in Figure 12.

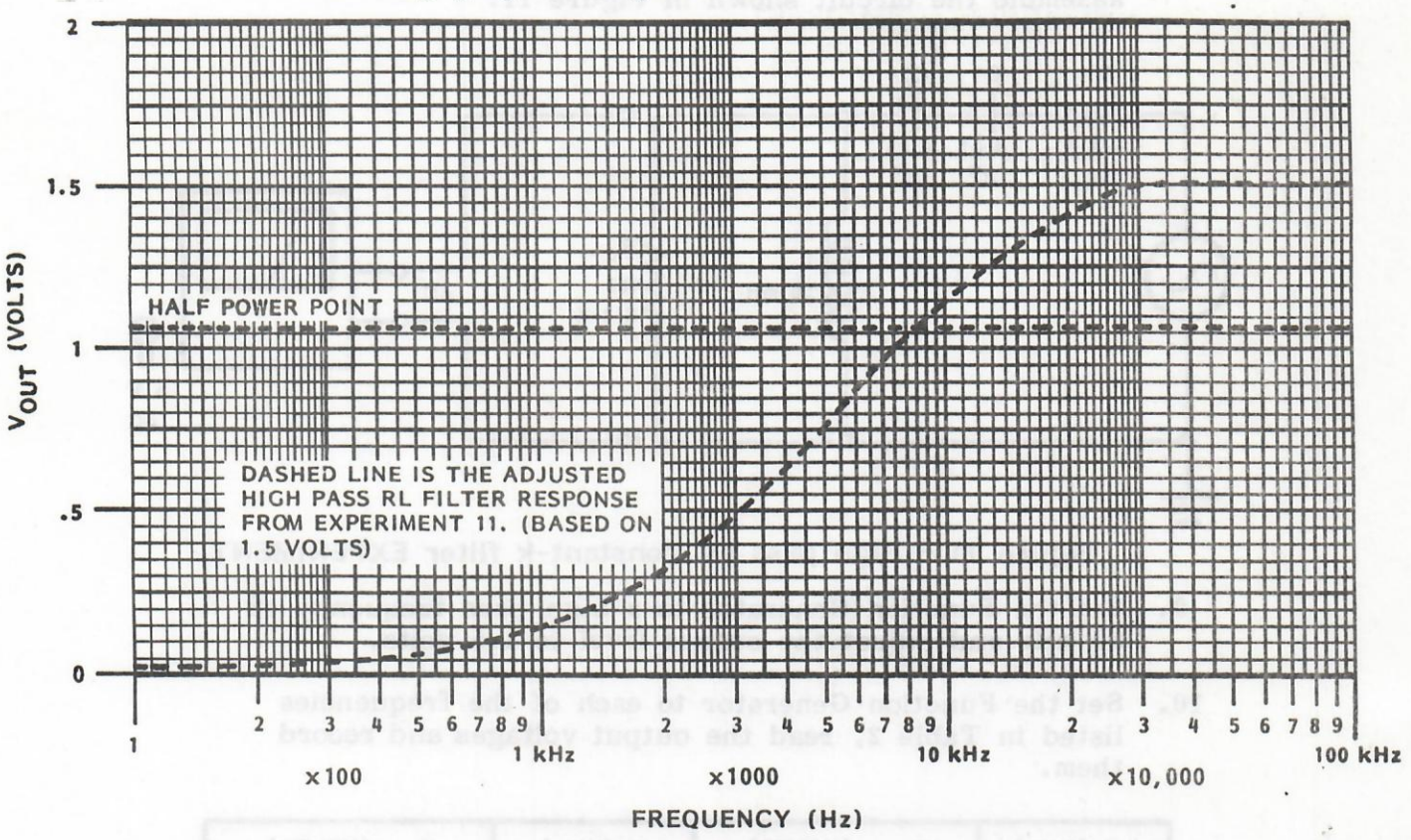


Figure 12 - Graph for plotting V_{OUT} versus frequency for the high pass constant-k LC filter; EXPERIMENT.

13.4 m-DERIVED FILTERS

12. Remove the present wiring and assemble the m-derived low pass filter circuit shown in Figure 13.

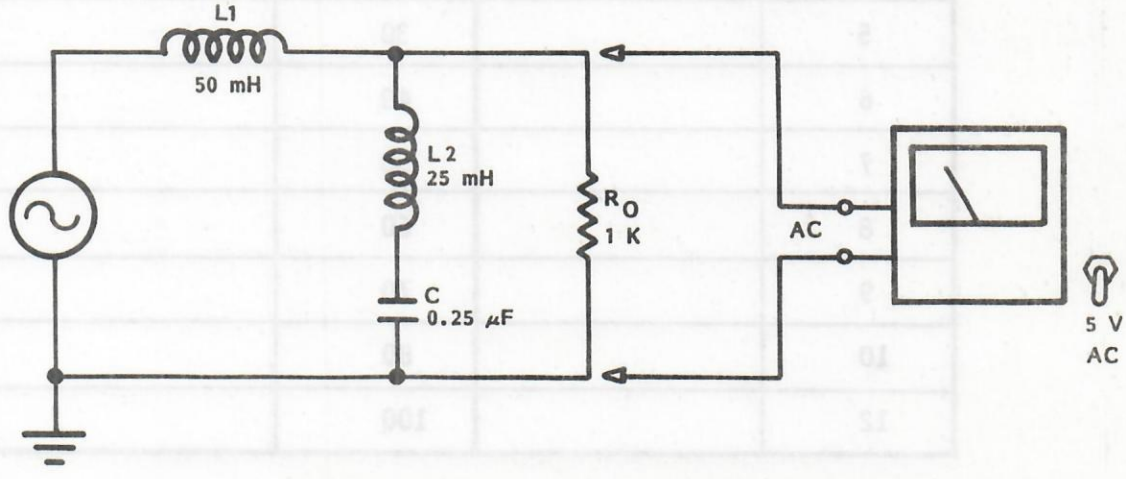


Figure 13 - M-derived low pass filter EXPERIMENT.

13. Set the Function Generator to a low pass frequency of 100 Hz and adjust the SINE AMPL. level for a 3 volt output from the filter.

14. Set the Function Generator to each of the frequencies listed in Table 3, read the output voltages and record them.

f (Hz)	V_{OUT} (VOLTS)	f (kHz)	V_{OUT} (VOLTS)
100	3	1200	
200		1400	
300		1600	
400		1800	
500		2000	
600		2200	
700		2500	
800		3000	
900		3500	
1000		4000	

TABLE 3 - V_{OUT} versus frequency for the m-derived low pass filter shown in Figure 13.

15. Measure the exact frequency of f_∞, the minimum output voltage value (which is close to 2 kHz) and record both the frequency and voltage level below.

f_∞= _____ Hz
$V_0 f_\infty$ = _____ V

16. Adjust the frequency control for maximum (peak or overshoot) output voltage (close to 1 kHz) and record the voltage value and frequency below.

V_{MAX} = _____ V f_{MAX} = _____ Hz

17. Calculate the cut-off voltage from the low frequency level of 3.0 volts at 100 Hz.

$$V_{fc} = (0.707)(V_{MAX})$$
$$= (0.707)(3.0)$$

V_{fc} = _____ V

18. Adjust the frequency upward from 1 kHz until V_O drops to this cut-off voltage of 2.12 volts, the f_c point. Record the cut-off frequency below.

f_c = _____ Hz

19. Plot the results obtained in steps 15, 16, 17 and 18 on the semi-log graph in Figure 14.

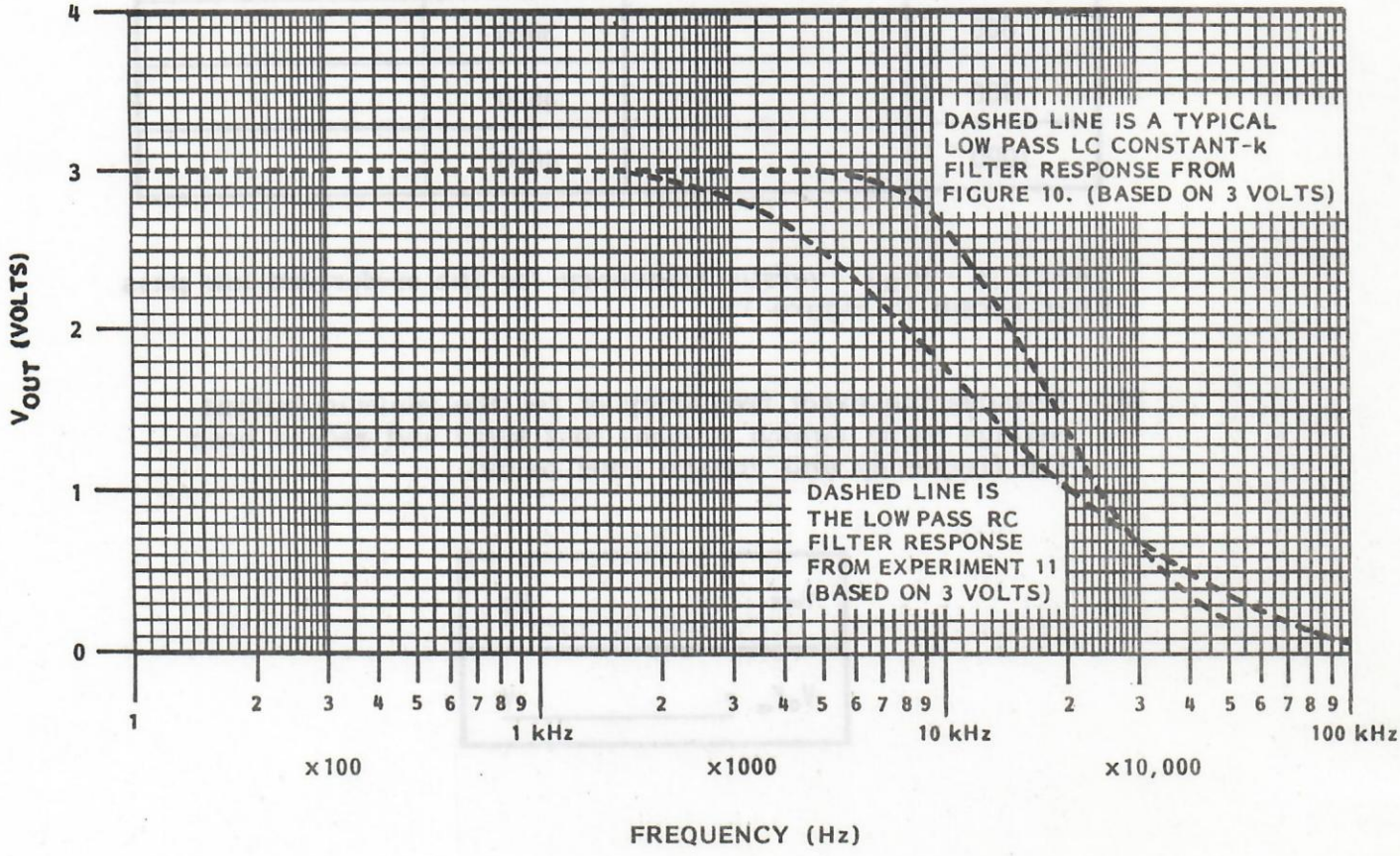

4
3
2
1
0
V_{OUT} (VOLTS)
DASHED LINE IS A TYPICAL LOW PASS LC CONSTANT-k FILTER RESPONSE FROM FIGURE 10. (BASED ON 3 VOLTS)
DASHED LINE IS THE LOW PASS RC FILTER RESPONSE FROM EXPERIMENT 11 (BASED ON 3 VOLTS)
1
2 3 4 5 6 7 8 9
1 kHz
2 3 4 5 6 7 8 9
10 kHz
2 3 4 5 6 7 8 9
100 kHz
x100
x1000
x10,000
FREQUENCY (Hz)

Figure 14 - Graph for plotting V_{OUT} versus frequency for the low pass m-derived filter; EXPERIMENT.

20. Compare the m-derived roll-off plotted in Figure 14 to the roll-off of the constant-k filter and the RL filter, both shown on the graph in dashed lines. How do they compare?

_____

_____

_____

_____

21. The calculated value of m based on measurements for the filter circuit shown in Figure 13 can be found using the equation:

$$m = \sqrt{1-\left(\frac{f_c}{f_\infty}\right)^2}$$

Insert the data from steps 15 and 18.

$$m = \sqrt{1 - \left(\frac{\quad}{\quad}\right)^2}$$

$$= \sqrt{1 - (\quad)^2}$$

$$= \sqrt{1 - (\quad)}$$

$$= \sqrt{(\quad)}$$

m = _____

This value of m should be in the range of 0.5 to 1.

CONCLUSIONS

We have learned from this experiment that:

LC circuits can be used as bandstop and bandpass filters.

LC components can be used to form a low pass or high pass constant-k filter network.

The roll-off characteristics of the constant-k filter are sharper than those of an RC or RL filter.

Varying the value of R_o will change the cut-off frequency in the LC filters.

LC filters can display an "overshoot" when the circuit Q is high.

M-derived filters have two frequency measurements, the cut-off frequency, f_c, and the infinite attenuation frequency, f_∞.

The m value of the filter is a function of the ratio of f_c and f_∞ and the value of m will fall between 1 and 0.5.

M-derived filters have a sharper roll-off characteristic than constant-k or RL and RC filters.

ASSIGNMENT

Answer the following multiple choice problems.

1. A parallel resonant circuit placed in series between the load and the source is a (an):

   a. bandpass filter.
   b. bandstop filter.
   c. constant-k filter.
   d. m-derived filter.

2. A parallel resonant circuit placed in parallel with the source will act as a (an):

   a. bandpass filter.
   b. bandstop filter.
   c. constant-k filter.
   d. m-derived filter.

3. A series resonant circuit wired in series between the source and the load is a (an):

   a. bandpass filter.
   b. bandstop filter.
   c. constant-k filter.
   d. m-derived filter.

4. A series resonant circuit wired in parallel with the source and load is a (an):

   a. bandpass filter.
   b. bandstop filter.
   c. constant-k filter.
   d. m-derived filter.

5. Electronic filters other than RLC circuits employ:

   a. crystals.
   b. ceramic.
   c. digital circuits.
   d. all of the above.

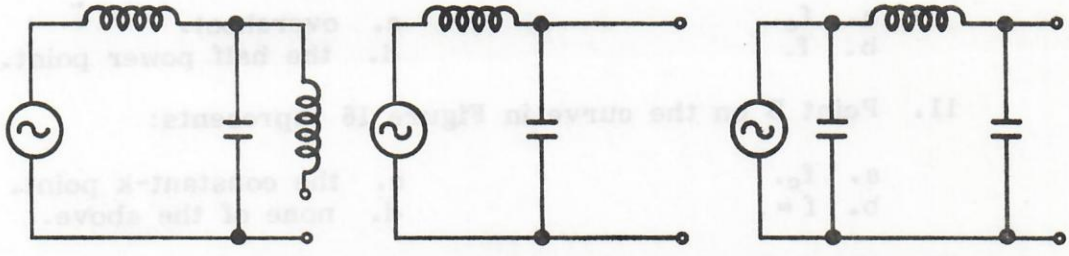


Figure 15 above refers to questions 6 to 8.

6. The filter configuration in Figure 15(a) is a (an):

   a. T.
   b. pi.
   c. L.
   d. series network.

7. The filter configuration in Figure 15(b) is a (an):

   a. T.
   b. pi.
   c. L.
   d. high pass.

8. The filter configuration in Figure 15(c) is a (an):

   a. T.
   b. pi.
   c. L.
   d. m-derived network.

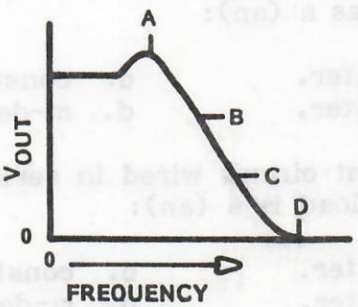


Figure 16 above refers to questions 9 to 12.

9. The response curve shown in Figure 16 is that of a:

   a. high pass m-derived filter.
   b. low pass m-derived filter.
   c. low pass RC filter.
   d. low pass constant-k filter.

10. Point A on the curve in Figure 16 represents:

    a. f_c.
    b. f.
    c. overshoot.
    d. the half power point.

11. Point B on the curve in Figure 16 represents:

    a. f_c.
    b. f_∞.
    c. the constant-k point.
    d. none of the above.

12. The infinite attenuation frequency of the filter in Figure 16 is marked by the letter:

    a. B.
    b. C.
    c. A.
    d. none of the above.

13. In the design of a constant-k filter, it is understood that:

    a. the configuration must be an L.
    b. R_i should equal R_o.
    c. C must equal 1/2 L.
    d. all of the above.

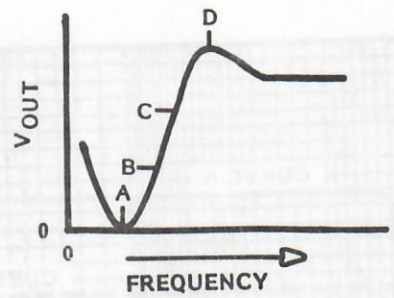


Figure 17 above refers to questions 14 to 16.

14. The response curve shown in Figure 17 is that of a:

a. high pass m-derived filter.
b. low pass m-derived filter.
c. high pass RL filter.
d. low pass constant-k filter.

15. Point C on the curve in Figure 17 represents:

a. overshoot.
b. f_∞.
c. f_c.
d. none of the above.

16. Point A on the curve in Figure 17 represents:

a. f_∞.
b. the infinite attenuation frequency.
c. both a and b.
d. neither a or b.

17. In an m-derived filter:

a. there are two critical frequency measurements.
b. the roll-off is steeper than that of an RL filter.
c. the normal value of m is usually close to 0.6.
d. all of the above.

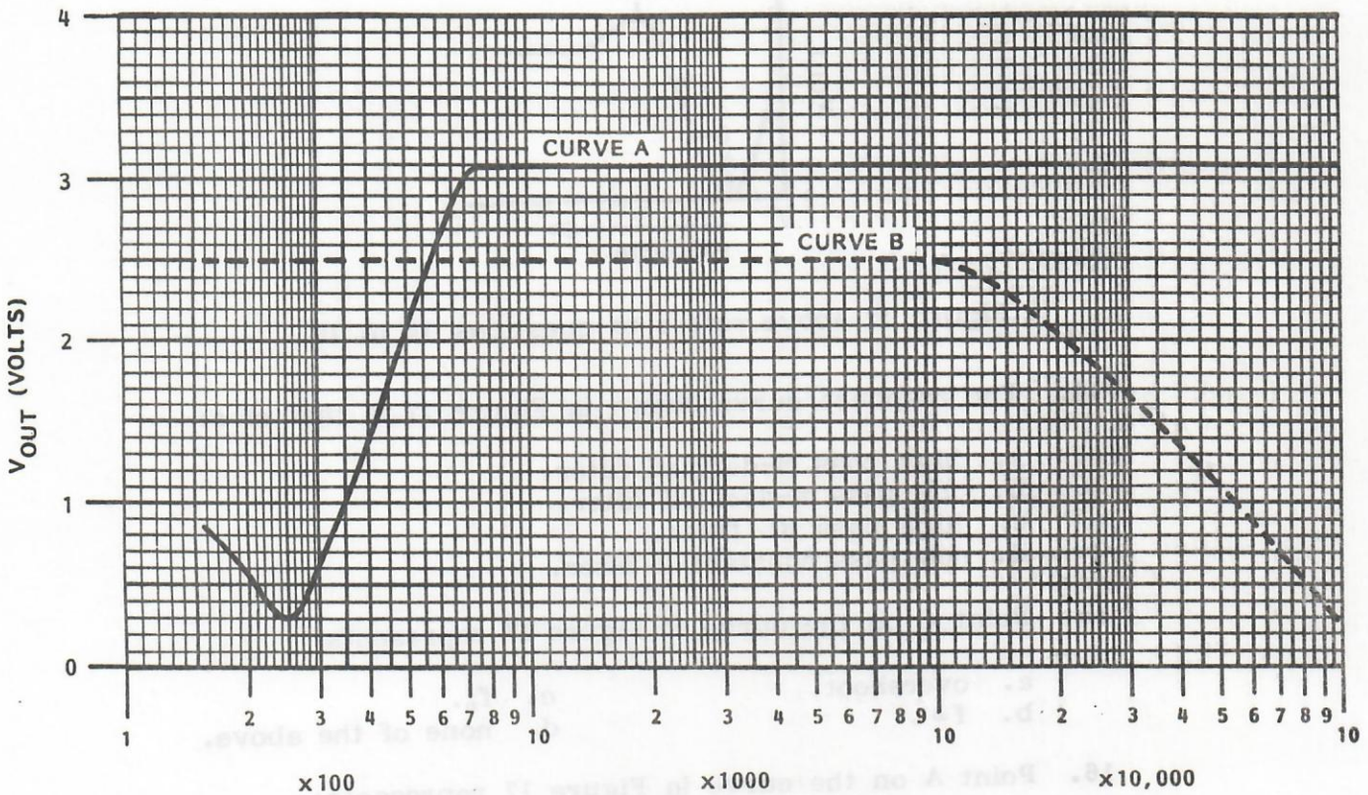


Figure 18 above refers to questions 18 to 20.

18. The cut-off frequency for curve A in Figure 18 is closest to:

a. 2.19 Hz.
b. 5.4 Hz.
c. 250 Hz.
d. none of the above.

19. The infinite attenuation frequency for curve A in Figure 18 is closest to:

a. 0.3 x 100 = 30 Hz.
b. 250 Hz.
c. 2.91 x 100 = 291 Hz.
d. 540 Hz.

20. Curve B in Figure 18:

a. is that of a low pass filter.
b. reaches f_c at 1.77 volts.
c. does not have an $f\infty$ point.
d. all of the above.

KEY TERMS

1. ATTENUATION

   A decrease in signal level.

2. BAND PASS FILTER

   A filter that passes a band of frequencies ($f_2 - f_1$) and blocks all frequencies above f_2 and all frequencies below f_1.

3. BAND STOP FILTER

   A circuit that blocks a band of frequencies ($f_2 - f_1$) and passes all frequencies above f_2 and all frequencies below f_1.

4. CONSTANT k FILTER

   An LC Filter in which k equals the product of X_C and X_L and is always constant for any operating frequency.

5. CUT OFF FREQUENCY

   The frequency at which the output signal level drops to half power or 70.7% of the maximum voltage.

6. HALF POWER POINT

   The frequency at which the output power drops to one half of maximum. If the output voltage is measured, the half power point occurs when the output voltage drops to 70.7% of the maximum voltage.

7. HIGH PASS FILTER

   A filter circuit that blocks all low frequencies below the cut off frequency, f_c, and passes all frequencies above f_c.

8. LOW PASS FILTER

   A filter circuit that blocks all high frequencies above f_c, the cut off frequency, and passes all frequencies below f_c.

9. L FILTER

   A filter circuit whose components are arranged in a L configuration.

10. m DERIVED FILTER

A filter circuit that employs reactive components and a resonant network that produces a frequency of infinite attenuation. m equals the ratio between f_c the cut off frequency, and $f\infty$, the frequency of infinite attenuation.

11. OVERSHOOT

A sudden, unexpected rise in the filter output just before the cut off frequency.

12. PARALLEL RESONANCE

A state that exists in a parallel circuit consisting of an ac voltage source, capacitance, and inductance when the frequency is such that X_L equals X_C.

13. PI FILTER

A filter circuit whose components are arranged in a pi (π) configuration.

14. RC FILTER

A filter circuit that contains resistors and capacitors.

15. RESONANT FILTER

A resonant circuit used to block or pass a group of frequencies.

16. RL FILTER

A filter circuit formed with resistors and inductors.

17. RLC FILTERS

A filter circuit formed with a combination of resistors, inductors and capacitors.

18. ROLL OFF

Also called slope, it is a gradual reduction of output above or below the f_c point of response.

19. SERIES RESONANCE

The state that exists in a series circuit consisting of an ac voltage source, capacitance, inductance and resistance when the frequency is such that X_L equals X_C.

Mutual Inductance 14

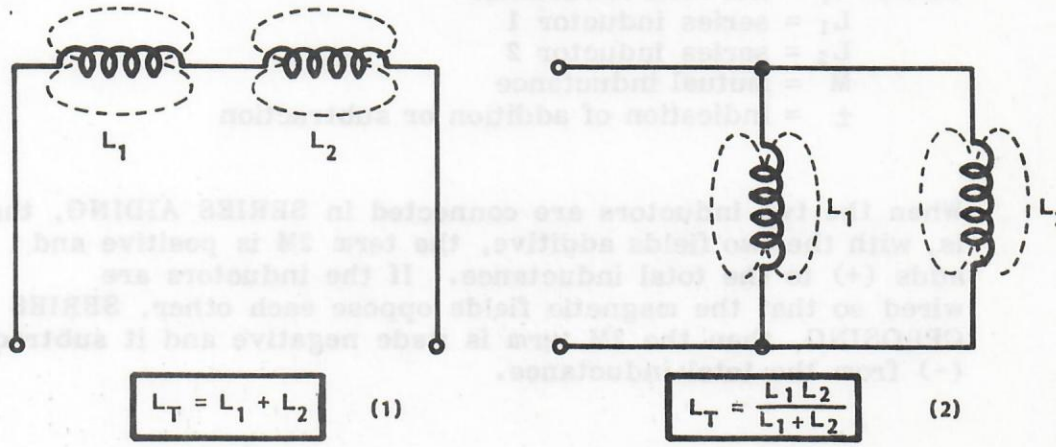
OBJECTIVES

When you finish this experiment, you will be able to:

1. Define what is meant by coupling.
2. Define what is meant by series aiding and series opposing inductors.
3. Explain what is meant by coefficient of coupling and mutual inductance.
4. Calculate the coefficient of coupling and the mutual inductance between two coupled inductors.
5. Calculate the coefficient of coupling and the mutual inductance between two decoupled inductors.

DESCRIPTION

When individual inductors are connected in series or parallel, as shown in Figure 1(a) and 1(b), and the magnetic lines of force generated in each inductor do not cut across the other inductor, the total inductances are given by the equations presented in earlier experiments and shown again in Figure 1.



$$L_T = L_1 + L_2 \quad (1)$$

(a) SERIES INDUCTORS

$$L_T = \frac{L_1 L_2}{L_1 + L_2} \quad (2)$$

(b) PARALLEL INDUCTORS

Figure 1 - Series and parallel connected inductors that are not coupled.

2—MUTUAL INDUCTANCE

If the inductors in the circuit are physically positioned so that the magnetic lines from each inductor cut across the other inductor as shown in Figure 2, equations (1) and (2), shown in Figure 1, are no longer valid. This interaction is called COUPLING and an additional inductance, called MUTUAL INDUCTANCE, is formed. It is measured in Henries and defined by the letter M.

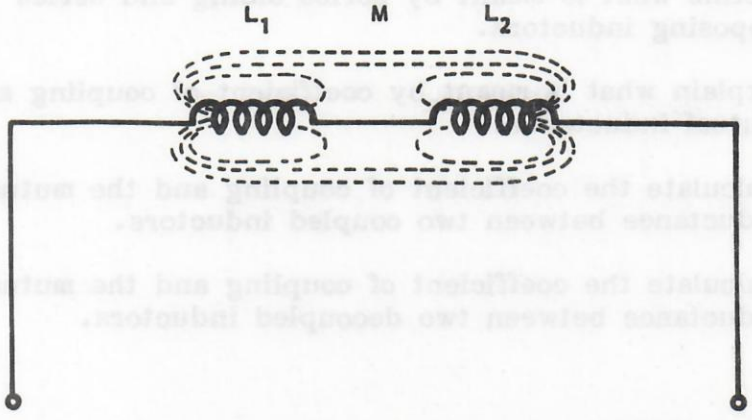


Figure 2 - Series inductors with mutual coupling.

When mutual coupling exists between two series inductors, the total inductance is given by the equation:

$$L_T = L_1 + L_2 \pm 2M \qquad (3)$$

where L_T = the total inductance
L_1 = series inductor 1
L_2 = series inductor 2
M = mutual inductance
$\pm$ = indication of addition or subtraction

When the two inductors are connected in SERIES AIDING, that is, with the two fields additive, the term 2M is positive and adds (+) to the total inductance. If the inductors are wired so that the magnetic fields oppose each other, SERIES OPPOSING, then the 2M term is made negative and it subtracts (-) from the total inductance.

COEFFICIENT OF COUPLING (k)

The COEFFICIENT OF COUPLING is a measurement of how many magnetic lines of flux from one coil reaches the other. The coefficient of coupling, designated by the letter k, can range from 0 to 1. At k = 0, no flux lines couple the two coils and at k = 1, every flux line generated by one coil cuts or couples with the second coil. If k = 0.5, then half the lines generated by one inductor couple to the second inductor.

The amount of mutual coupling between two coils depends on how close they are to each other. It also depends on their relative angles; coupling is maximum when they are parallel and minimum or zero when they are at right angles.

CALCULATING M

When the coefficient of coupling, k, is known, the mutual inductance, M, can be calculated using equation (4).

$$M = k\sqrt{L_1 L_2} \tag{4}$$

where M = the mutual inductance in the same unit as L_1 and L_2
k = the coefficient of coupling
L_1 = series inductor 1
L_2 = series inductor 2

MEASURING M

When the coefficient of coupling is unknown, M can be calculated from measurements using equation (5) below which can be derived from the earlier equation (3).

$$M = \frac{L_{MAX} - L_{MIN}}{4} \tag{5}$$

where M = mutual inductance
L_{MAX} = the total inductance with aiding fields ($L_1 + L_2 + 2M$)
L_{MIN} = the total inductance with opposing fields ($L_1 + L_2 - 2M$)

CALCULATING k

The value of L_{MIN} and L_{MAX} can be measured via an experiment so that M can be calculated. Once M, L_1 and L_2 are known, k can be found, as shown below, using equation (4a).

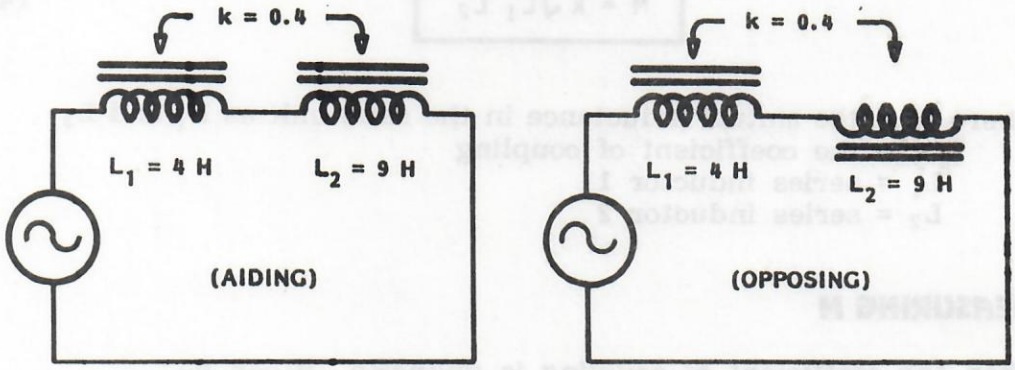
$$M = k\sqrt{L_1 L_2} \tag{4}$$

Transposing for k:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{4a}$$

CALCULATING M AND L

Two inductors are connected in series aiding as shown in Figure 3. A coefficient of coupling of 0.4 is given as shown. This means that 40% of the generated flux is coupled between the two inductors.



(a) INDUCTORS SERIES AIDING (b) INDUCTORS SERIES OPPOSING

Figure 3 – Inductors wired in series aiding and opposing.

The mutual inductance for the circuit of Figure 1 is calculated below:

$$M = k\sqrt{L_1 L_2} \tag{4}$$

$$= 0.4\sqrt{(4)(9)}$$

$$= 0.4\sqrt{36}$$

$$M = 2.4 \text{ H}$$

The total inductance for the "aiding" circuit of Figure 3(a) will be:

$$L_{MAX} = L_1 + L_2 + 2M \qquad (3)$$

$$= 4 + 9 + 2(2.4)$$

$$\boxed{L_{MAX} = 17.8 \text{ H}}$$

If the inductors are wired series "opposing" as shown in Figure 3(b), then the total inductance will be:

$$L_{MIN} = L_1 + L_2 - 2M \qquad (3)$$

$$= 4 + 9 - 2(2.4)$$

$$\boxed{L_{MIN} = 8.2 \text{ H}}$$

If the coupling, k, is unknown but L_{MAX} and L_{MIN} are measured, then k can be calculated as shown below.

$$M = \frac{L_{MAX} - L_{MIN}}{4} \qquad (5)$$

$$= \frac{17.8 - 8.2}{4} = \frac{9.6}{4}$$

$$\boxed{M = 2.4 \text{ H}}$$

Then:

$$k = \frac{M}{\sqrt{L_1 L_2}} \qquad (4a)$$

$$= \frac{2.4}{\sqrt{(4)(9)}}$$

$$= \frac{2.4}{\sqrt{36}} = \frac{2.4}{6}$$

$$\boxed{k = 0.4}$$

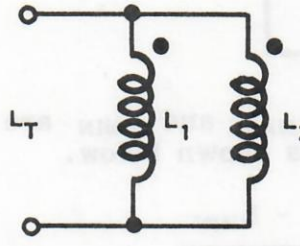
PARALLEL COUPLED INDUCTORS

When two inductors are wired in parallel without any mutual coupling, the total inductance is given by:

$$L_T = \frac{L_1 L_2}{L_1 + L_2} \qquad (2)$$

If, however, the two inductors are magnetically coupled, equation (2) above, is no longer valid. The effective inductance, L_T, can be found from one of two equations that follow.

INDUCTORS WIRED IN PARALLEL AIDING



$$L_T = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} \qquad (6)$$

Given that L_1 and L_2 both equal 2 H, and that M equals 0.5 H, the parallel combination wired series aiding, will have an L_T of:

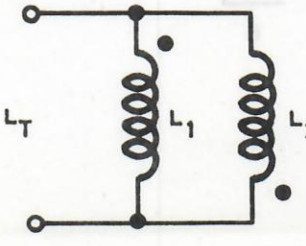
$$L_T = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M}$$

$$= \frac{(2)(2) - 0.5^2}{2 + 2 - 2(0.5)}$$

$$= \frac{4 - 0.25}{3}$$

$$L_T = 1.25 \text{ H}$$

INDUCTORS WIRED IN PARALLEL OPPOSING



$$L_T = \frac{L_1 L_2 - M^2}{L_1 + L_2 + 2M} \qquad (7)$$

Given that L_1 and L_2 both equal 2 H, and that M equals 0.5 H, the parallel combination, wired series opposing, will have an L_T of:

$$L_T = \frac{L_1 L_2 - M^2}{L_1 + L_2 + 2M}$$

$$= \frac{(2)(2) - 0.5^2}{2 + 2 + 2(.5)}$$

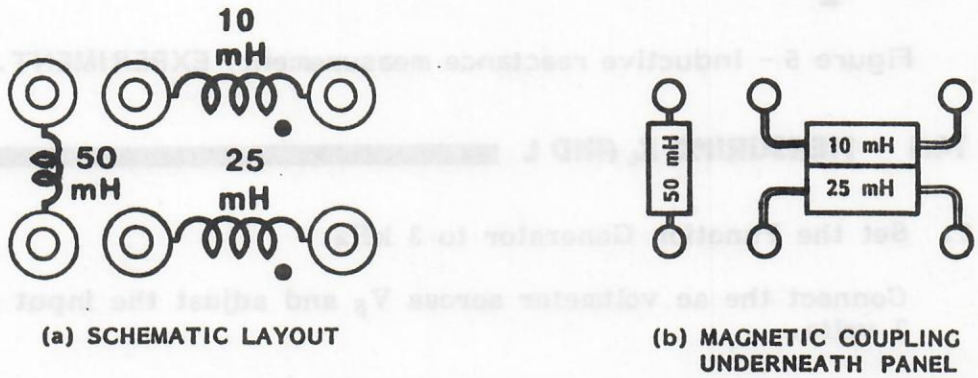
$$= \frac{4 - 0.25}{5}$$

$$\boxed{L_T = 0.75 \text{ H}}$$

Observe that when the inductor fields oppose each other, the effective parallel inductance is lower than when the fields are aiding each other.

Ed-Lab INDUCTOR POSITIONS

There are three inductors mounted on the Ed-Lab 651 panel, 10 mH, 25 mH and 50 mH. Their panel positions are shown in Figure 4(a).



(a) SCHEMATIC LAYOUT

(b) MAGNETIC COUPLING UNDERNEATH PANEL

Figure 4 - Schematic and physical layout of the inductors.

The 10 mH and 25 mH inductors are physically parallel for the maximum amount of coupling (k). The 50 mH inductor is placed at right angles to the 10 mH and 25 mH inductors for minimum coupling or a k of zero. The dots at one end of the inductor symbols are called SENSE DOTS and indicate the direction of coupling between the two coils.

NOTE: For this experiment to work, the coils mounted on the panel must be positioned as shown in Figure 4(b). Early models of the Ed-Lab 650 do not have the 10 mH and 25 mH coils coupled to each other as shown and must be physically modified inside the trainer if this experiment is to be done.

PROCEDURE

1. Wire the circuit shown in Figure 5.

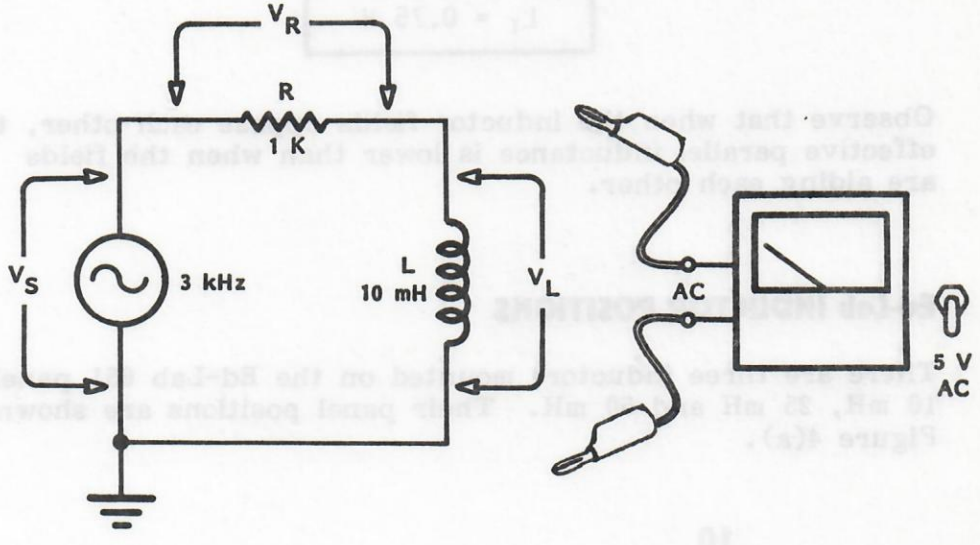


Figure 5 - Inductive reactance measurement; EXPERIMENT.

14.1 MEASURING X_L AND L

2. Set the Function Generator to 3 kHz.

   Connect the ac voltmeter across V_S and adjust the input to 3 volts.

3. Connect the voltmeter across the 1 K resistor and record the voltage reading in the V_R column of Table 1.

INDUCTOR	MEASURE		CALCULATE	
	V_R	V_L	$X_L = \frac{V_L}{V_R}(R)$	$L = \frac{X_L}{2\pi f}$
L1 = 10 mH				
L2 = 25 mH				
L3 = 50 mH				

TABLE 1 - Data for calculation of X_L and L.

4. Measure the voltage drop, V_L, across the inductor and enter the reading in the V_L column of Table 1.

5. Calculate X_L for the 10 mH inductor from the data listed in Table 1.

$$X_L = \frac{V_L}{I_L}$$

$$X_L = \frac{V_L}{V_R}$$

$$X_L = V_L \frac{R}{V_R}$$

When R is equal to 1 K, the above equation can be simplified to:

$$X_L = \frac{V_L}{V_R}(K)$$

Calculate X_{L1} using the data from Table 1.

$$X_{L1} = \frac{(\quad)}{(\quad)}\,(K)$$

X_{L1} = _____ K

Enter this reactance value in the X_L column of Table 1.

6. Calculate the inductance for L_1 from the measured values as follows:

$$L = \frac{X_L}{2\pi f}$$

$$= \frac{(\quad)}{(6.28)(3000)}$$

$$= \frac{(\quad)}{(\quad)}$$

L = _____ H or _____ mH

Enter the results in Table 1.

How close is the measured inductance to the rated inductance?

_____

_____

7. Replace the 10 mH inductor with the 25 mH inductor and then with the 50 mH inductor and repeat the measurements and calculations for each, entering the results in Table 1.

How close are the measured inductances for the 25 and 50 mH inductors?

_____

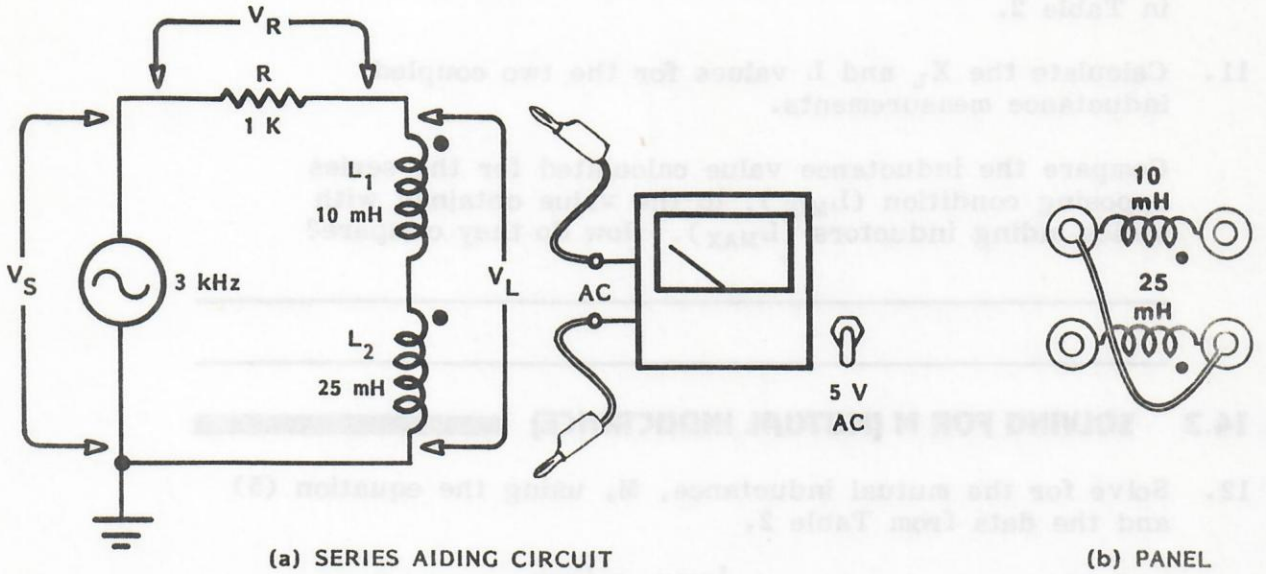
_____

_____

_____

14.2 MEASURING L_{MAX} AND L_{MIN}

8. Modify the circuit wired on the trainer panel to that shown in Figure 6(a) and (b).



(a) SERIES AIDING CIRCUIT (b) PANEL

Figure 6 - Mutual inductance circuit EXPERIMENT.

9. Take the readings for V_R and V_L and enter the data in the first line of Table 2, Series Aiding, L_{MAX}.

INDUCTORS	MEASURE		CALCULATE	
	V_R	V_L	$X_L = \frac{V_L}{V_R}(R)$	$L = \frac{X_L}{2\pi f}$
SERIES AIDING L_{MAX}				
SERIES OPPOSING L_{MIN}				

TABLE 2 - Series aiding and opposing measurements.

10. Reverse the leads on the 25 mH inductor creating a Series Opposing condition between L_1 and L_2.

    Repeat the V_R and V_L measurements, entering the results in Table 2.

11. Calculate the X_L and L values for the two coupled inductance measurements.

    Compare the inductance value calculated for the series opposing condition (L_{MIN}), to the value obtained with series aiding inductors (L_{MAX}). How do they compare?

_____

_____

14.3 SOLVING FOR M (MUTUAL INDUCTANCE)

12. Solve for the mutual inductance, M, using the equation (5) and the data from Table 2.

$$M = \frac{L_{MAX} - L_{MIN}}{4} \qquad (5)$$

$$= \frac{(\quad) - (\quad)}{4}$$

MUTUAL INDUCTANCE	M = _____ mH

14.4 SOLVING FOR k (COEFFICIENT OF COUPLING)

13. Now that M is known, it is possible to solve for k.

    Solve for k using equation (4a) below:

$$k = \frac{M}{\sqrt{L_1 \; L_2}} \qquad (4a)$$

$$= \frac{(\quad)}{\sqrt{(10)(25)}}$$

$$= \frac{(\quad)}{\sqrt{250}}$$

k = _____

The value of k should be between 0 and 1. Does your answer fall in this range?

Would you consider this coupling to be "loose" or "tight"?

14.5 SERIES INDUCTORS WITH k = 0 (OPTIONAL)

14. Modify the circuit on the panel by substituting the 50 mH inductor for the 10 mH inductor as shown in Figure 7.

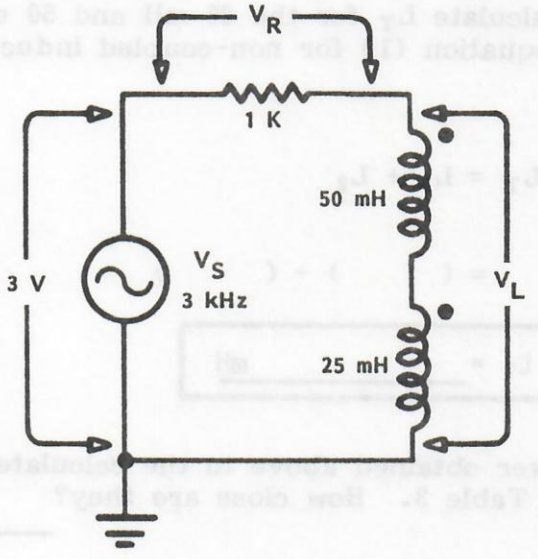


Figure 7 - Series inductors without coupling; EXPERIMENT.

15. Check to see that V_S is equal to 3 volts at 3 kHz.

16. Read V_R and V_L and enter the values in the first line of Table 3.

INDUCTOR	MEASURE		CALCULATE	
	V_R	V_L	$X_L = \frac{V_L}{V_R}(R)$	$L = \frac{X_L}{2\pi f}$
DIRECTION 1				
DIRECTION 2				

TABLE 3 - Series 50 mH and 25 mH data.

17. Reverse the leads to the 50 mH inductor. Repeat the voltage measurements and enter the readings in the second line of Table 3.

18. Compare the voltages on line 1 to line 2. Are they different?

_____

What does this indicate?

_____

_____

19. Calculate X_L and L for the values in Table 3 and enter them in the Table. Calculate L_T for the 25 mH and 50 mH inductors using equation (1) for non-coupled inductors as shown below.

$$L_T = L_1 + L_2 \qquad (1)$$

$$= (\quad) + (\quad)$$

$L_T =$ _____ mH

Compare the answer obtained above to the calculated value of L_T from Table 3. How close are they?

_____

_____

_____

20. Solve for M and k using equations (5) and (4a) shown below:

$$M = \frac{L_{MAX} - L_{MIN}}{4} \qquad (5)$$

$$= \frac{(\quad) - (\quad)}{4}$$

M = _____ H

$$k = \frac{M}{\sqrt{L_1 - L_2}} \qquad (4a)$$

$$= \frac{(\quad)}{\sqrt{(50) - (25)}}$$

k = _____

14.6 MUTUAL INDUCTANCE WITH AN IRON CORE (OPTIONAL)

This part of the experiment requires the use of the CES 306 Transformer Module plug-in card.

21. Plug the CES 306 Transformer Card into the PC socket on the Ed-Lab trainer panel.

Wire the circuit shown in Figure 8.

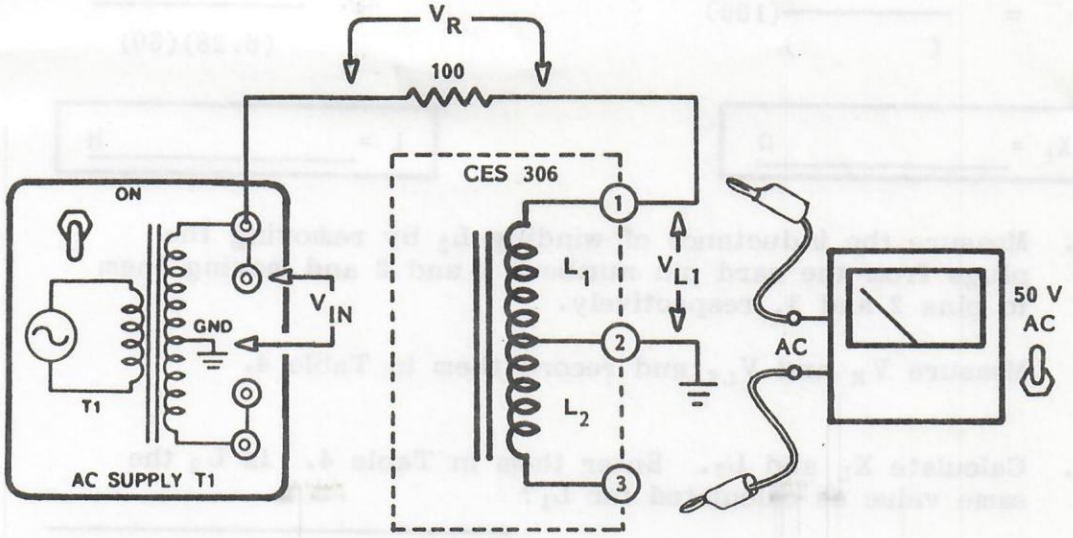


Figure 8 - Mutual inductance test on an iron core inductor; EXPERIMENT.

22. Measure the inductance of L_1 of the power transformer (Figure 8) by measuring V_R and V_{L1} (from pin 1 to pin 2 on the PC jack pin-out).

Enter the voltage readings in Table 4.

TRANSFORMER WINDINGS	MEASURE			CALCULATE	
	V_{IN}	V_R	V_L	$X_L = \frac{V_L}{V_R}(R)$	$L = \frac{X_L}{2\pi f}$
L_1 (1 to 2)					
L_2 (2 to 3)					
L1 + L2 (1 to 3)					

TABLE 4 - Power transformer inductance measurements.

23. Calculate X_L and L for the L_1 winding and enter the values in Table 4 on line L_1. The frequency, f, is 60 Hz.

$$X_L = \frac{V_L}{V_R}(R) \qquad L = \frac{X_L}{2\pi f}$$

$$= \frac{(\quad)}{(\quad)}(100) \qquad = \frac{(\quad)}{(6.28)(60)}$$

$X_L =$ _____ Ω

$L =$ _____ H

24. Measure the inductance of winding L_2 by removing the plugs from the card pin numbers 1 and 2 and moving them to pins 2 and 3, respectively.

Measure V_R and V_{L2} and record them in Table 4.

25. Calculate X_L and L_2. Enter them in Table 4. Is L_2 the same value as calculated for L_1?

_____

_____

Why?

_____

_____

26. Change the circuit to measure the full series winding, L_1 plus L_2, as shown in Figure 9 by connecting the wire plugs to pins 1 and 3.

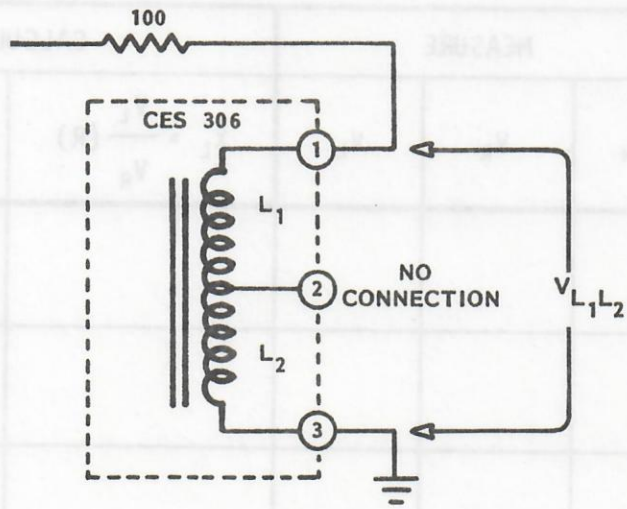


Figure 9 - Measuring the inductance of the full winding; EXPERIMENT.

27. Measure V_R and V_L For the full L_1 plus L_2 winding and enter the results in Table 4.

28. Calculate X_L and L for the full L_1 plus L_2 winding.

$$X_L = \frac{V_L}{V_R}(R) \qquad L_T = \frac{X_L}{2\pi f}$$

$$= \frac{(\quad)}{(\quad)}(100) \qquad = \frac{(\quad)}{(6.28)(60)}$$

$X_L =$ _____ Ω $\qquad$ $L_T =$ _____ H

Does the total inductance, L_T, equal $L_1 + L_2$ and why?

_____

_____

_____

29. Calculate the Mutual Inductance, M, from the above using equation (3) transposed to solve for M.

$$L_T = L_1 + L_2 + 2M \qquad (3)$$

$$M = \frac{L_T - L_1 - L_2}{2}$$

$$= \frac{(\quad) - (\quad) - (\quad)}{2}$$

$M =$ _____ H

30. Solve for k using equation (4a).

$$k = \frac{M}{\sqrt{L_1 L_2}}$$ ← (From Step 29) ← (From Table 4)

$$= \frac{(\qquad)}{\sqrt{(\qquad)(\qquad)}}$$

$$k = \_\_\_\_\_$$

The coefficient of coupling, k, calculated above, should be high, between 0.8 and 1. This is because the presence of the iron core in the transformer transfers a high percentage of the flux lines between each winding and the windings are very closely coupled.

CONCLUSIONS

We have learned from this experiment that:

The total inductance of two series inductors that are not magnetically coupled, equals:

$$L_T = L_1 + L_2$$

The total inductance of two series inductors that are coupled, is equal to:

$$L_T = L_1 + L_2 + 2M$$

The coefficient of coupling, k, between two inductors is a measure of how many magnetic lines of force from one inductor reaches the other inductor.

The coefficient of coupling ranges from 0 to 1.

The mutual inductance between two magnetically coupled inductors is equal to:

$$M = k\sqrt{L_1 L_2}$$

When L_{MAX} and L_{MIN} are known, M, the mutual coupling, can be calculated from:

$$M = \frac{L_{MAX} - L_{MIN}}{4}$$

When the mutual coulping, M, is known, k can be calculated from:

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

Inductors that are placed at right angles to each other have a k of 0.

ASSIGNMENT

Answer the following multiple choice questions.

1. Two inductors, each rated at 250 mH, are wired in series aiding and placed at right angles (90°) to each other. The total inductance can be determined from:

   a. $L_1 + L_2$ multiplied by a k of .90 or 450 mH.
   b. $L_1 + L_2 + M$ where M equals 90 or 590 mH.
   c. $L_1 + L_2$ or 500 mH.
   d. none of the above.

2. In order to get the highest mutual inductance between two inductors they must be wired in series_____ and placed _____.

   a. aiding; in parallel.
   b. aiding; at right angles.
   c. opposing; in parallel.
   d. opposing; at right angles.

3. Two inductors, 9 H and 12 H, are wired in series opposing and have a mutual inductance of 3 H. The total inductance is equal to:

   a. 21 H.
   b. 3 H.
   c. 9 H.
   d. 15 H.

4. A 2,000 mH and 4.5 H inductor are wired in series aiding and positioned to produce a k of 0.6. The mutual inductance developed equals:

   a. 1.8 k.
   b. 3.9 H.
   c. 6.5 H.
   d. 1.8 H.

5. Two inductors, when wired in series opposing, have a total inductance of 5.8 H and when wired in series aiding, have a total of 10 H. The mutual inductance between the two inductors is:

   a. 1.05 H.
   b. 2.1 H.
   c. 3.95 H.
   d. 7.9 H.

6. Two inductors, one 3 H and the other unknown, are connected in series for a total of 12 H with a mutual inductance of 1H, aiding. The value of the second inductor is:

a. 4 H.
b. 7 H.
c. 10 H.
d. 17 H.

7. A 30 mH inductor and a 70 mH inductor are wired in series aiding and develop a mutual inductance of 25 mH. The coefficient of coupling is closest to:

a. 0.25
b. 0.5
c. 0.55
d. 0.7

KEY TERMS

1. COEFFICIENT OF COUPLING (k)

   The amount of magnetic coupling between two inductors defined as k, and ranging from 0 to 1.

2. LOOSE COUPLING

   Two inductors positioned so that very few magnetic lines of force are coupling between them.

3. MUTUAL INDUCTANCE (M)

   A measure of the voltage induced in coil A by changing flux in coil B. The mutual inductance, M, measured in Henries, is determined by the values of coil A and B and the coefficient of coupling, k.

4. SENSE DOTS

   A marking on the inductor symbol that indicates the start of the winding in relation to other inductors.

5. SERIES AIDING

   When two inductors are wired in series and positioned so that the magnetic fields are additive, they are wired series aiding.

6. SERIES OPPOSING

   When two inductors are wired in series and positioned so that the magnetic fields cancel, they are wired series opposing.

7. TIGHT COUPLING

   Two inductors positioned so that the maximum number of magnetic lines of force couple between them.

Power Factor Measurements 15

OBJECTIVES

When you finish this experiment you will be able to:

1. Explain why capacitors and inductors consume no power.
2. Calculate the consumption of ac power when the load is purely resistive.
3. Calculate the apparent power when the load is reactive.
4. Determine the Power Factor for a reactive circuit.
5. Develop a Power Factor correction circuit to reduce the apparent power drain.

ADDITIONAL EQUIPMENT REQUIRED

CES 306 Power Transformer Module (Optional)

DESCRIPTION

In a dc circuit, power is equal to the product of Voltage times Current and is expressed as:

$$P = E \cdot I$$

The calculated power is that used or dissipated by a component or supplied by the source. This is illustrated in Figure 1.

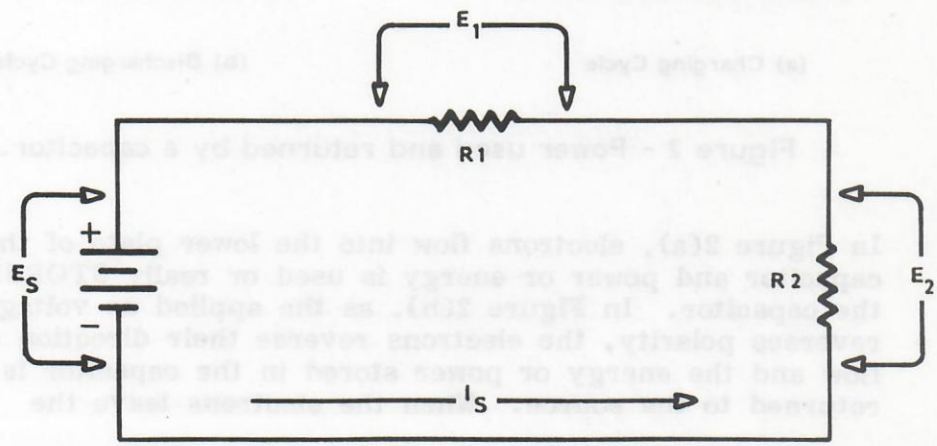


Figure 1 - Basic dc resistive circuit.

The power dissipated by the components and the source in Figure 1 can be expressed as:

$P_1 = E_1 \cdot I_S$ [POWER DISSIPATED, LOST OR USED IN RESISTOR R1]

$P_2 = E_2 \cdot I_S$ [POWER DISSIPATED, LOST OR USED IN RESISTOR R2]

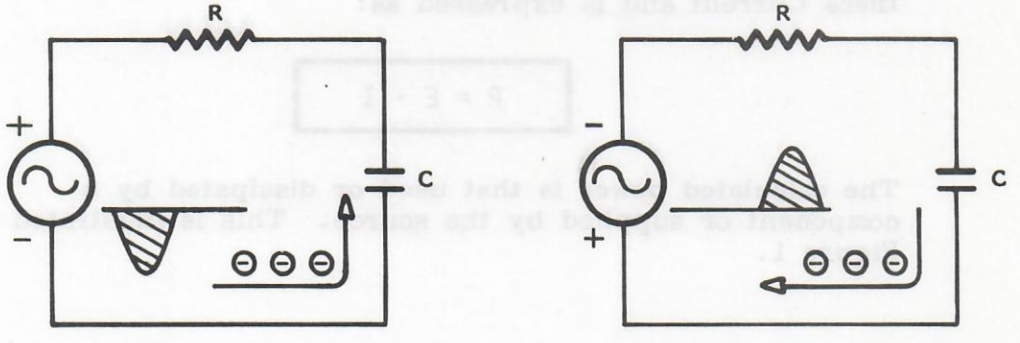
$P_S = E_S \cdot I_S$ [POWER SUPPLIED BY THE BATTERY OR POWER SOURCE]

Thus, if E · I is the power used by each component and P_S is the total power supplied by the source, then:

$$P_S = P_1 + P_2$$

POWER IN AC CIRCUITS

In an ac circuit, the power at any "instant of time" is also the product of Voltage times Current. Consider the circuit shown in Figure 2.



(a) Charging Cycle (b) Discharging Cycle

Figure 2 - Power used and returned by a capacitor.

In Figure 2(a), electrons flow into the lower plate of the capacitor and power or energy is used or really STORED in the capacitor. In Figure 2(b), as the applied ac voltage reverses polarity, the electrons reverse their direction of flow and the energy or power stored in the capacitor is returned to the source. When the electrons leave the

negative terminal of any device or component, power is being supplied. Thus, it may be said that a capacitor does not use or dissipate power but alternately stores and releases power.

Examine waveforms (a) and (b) in Figure 3. The current in a capacitor (waveform b) leads the voltage (a) by 90°. The instantaneous power generated by the voltage and current (a and b) is shown by waveform (c). The power in the capacitor alternates between plus and minus and the average power consumed is zero.

Inductors also store energy and power, but in a magnetic field rather than an electric field. The power is then returned to the circuit so that no power is used by an inductor or a capacitor. There is, of course, power used at all times by a resistor connected across an ac source because E and I are always in phase, that is, both plus or both minus so that the product is always positive.

AC POWER

If an ac load is purely resistive, then the power dissipated is given by:

$$P = (E_{rms})(I_{rms})$$

Thus, if the ac power line in a home or factory is 120 volts and a purely resistive load draws 10 amperes, the power being used, and being paid for, is:

$$P = (120)(10)$$

$$\boxed{P = 1{,}200 \text{ watts}}$$

If the load is not purely resistive but also contains inductance such as a motor or a ballast (a ballast is an inductor used in fluorescent lights), the power dissipated by the resistance is all that is used. The power, however, accepted by the inductance, which is returned to the circuit, must also be paid for. The total power is billed to you by the power company.

For example, consider the load shown in Figure 4, a motor used in a factory. It has dc resistance of 1 ohm and an inductance from the armature winding.

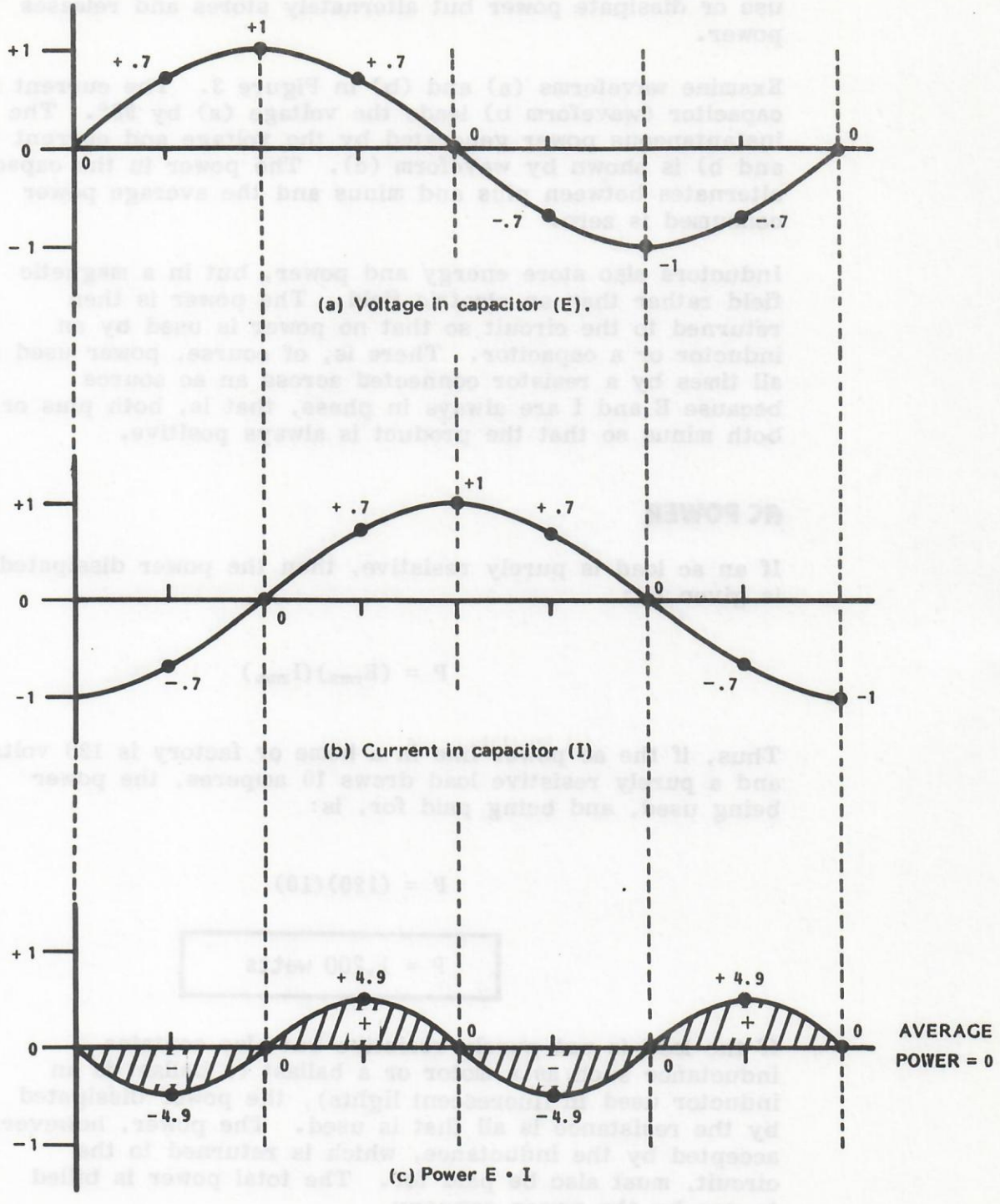


Figure 3 - Power stored and supplied by a capacitor.

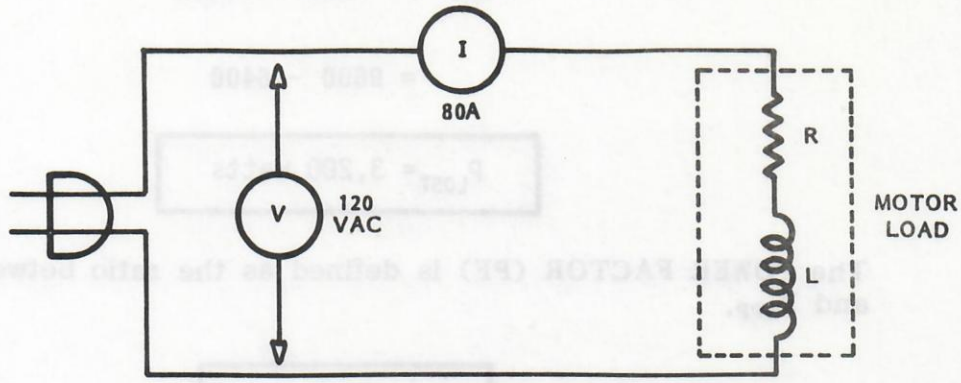


Figure 4 - Ac load with R and L.

With a dc resistance of 1 ohm, the "real" or TRUE POWER dissipated by the resistance is:

$$P_{TRUE} = I^2 R$$

$$= (80)^2 (1)$$

$$P_{TRUE} = 6{,}400 \text{ watts}$$

The power the circuit "appears" to use is called the APPARENT POWER and is the product of the source voltage, 120 volts, and the measured current drain, 80 amperes.

Because the apparent power is not real or true power, its unit is called VOLT-AMPERES, VA, instead of watts. The apparent power, then is:

$$P_{APPARENT} = E \cdot I$$

$$= (120)(80)$$

$$P_{Apparent} = 9{,}600 \text{ VA}$$

The lost power, which is paid for, is the difference between P_{TRUE} and $P_{APPARENT}$ and, for this example, is equal to:

$$P_{LOST} = P_{APP} - P_{TRUE}$$

$$= 9600 - 6400$$

$$\boxed{P_{LOST} = 3{,}200 \text{ watts}}$$

The POWER FACTOR (PF) is defined as the ratio between P_{TRUE} and P_{APP}.

$$\boxed{PF = \frac{P_{TRUE}}{P_{APP}}}$$

The power factor for the example shown in Figure 5, is:

$$PF = \frac{6400}{9600}$$

$$\boxed{PF = 0.666}$$

When the PF and the apparent power are known, the true power is determined from:

$$P_{TRUE} = (P_{APP})(PF)$$

$$= (9600)(0.666)$$

$$\boxed{P_{TRUE} = 6{,}400 \text{ watts}}$$

It is desired to have a power factor equal to 1 so that we only pay for the power used. When the power factor equals 1, the true and apparent powers are equal. In general, in industrial applications using motors and transformers, the power factor will always be less than 1.

POWER FACTOR CALCULATIONS

As noted earlier, the power factor of a circuit is determined from:

$$PF = \frac{P_{TRUE}}{P_{APP}}$$

The true power dissipated is a function of the circuit resistance while the apparent power dissipated is a function of the circuit impedance. Thus, the PF can also be expressed as:

$$PF = \frac{P_{TRUE}}{P_{APP}} = \frac{R}{Z}$$

Expanding on this, you will recall from Information Sheet 1 of this unit, that the circuit phase angle, θ, is also a function of the resistance and impedance where:

$$\theta = \text{arc cos } \frac{R}{Z}$$

Thus, if the phase angle of an RL circuit is known, the ratio of R to Z, the PF, can be determined from:

$$PF = \cos \theta$$

POWER FACTOR CORRECTION

An industrial plant cannot rid itself of the inductances that cause a low power factor. The plant requires transformers and motors to operate. Since the inductive effect (a lagging current) of all the devices on the line cannot be eliminated, the effect can be overcome by any device that offers a leading current and that device is a CAPACITOR. The capacitor is a power factor correction device and is placed in parallel with the factory inductive load. The value of the capacitor is chosen so that its reactive current is as close to or equal to the inductive current to produce a PF of 1. The capacitor stores the current or energy released by the inductor and then returns the energy to the inductor. This is shown in Figure 5.

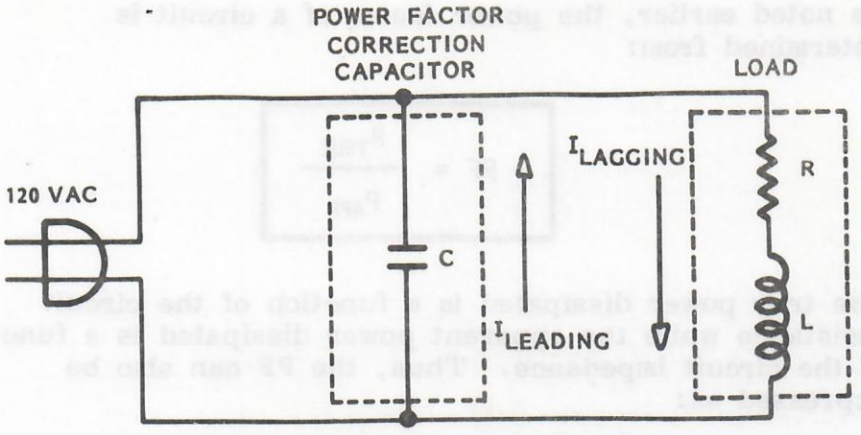


Figure 5 - Power factor correction capacitor.

The power factor correction capacitor is not rated in microfarads but in KVAR (kilovolt amperes reactive) indicating how much reactive current the capacitor can supply. A capacitor rated for 10 KVAR will cancel 10 KVAR of inductor reactive power bringing the circuit closer to pure resistive (PF = 1). If the capacitor chosen, unintentionally exceeds the inductive current, a LEADING power factor will be established.

It can be seen from Figure 5 and from the above description, that the correction capacitor and the inductive load form a PARALLEL RESONANT CIRCUIT as described earlier in Experiment No. 9. Energy is exchanged between the inductor and the capacitor with the source, V_S, supplying only that current dissipated in the circuit resistance or P_{TRUE}. This produces a PF of 1 and only occurs when the value of C is exactly correct to create resonance, a very difficult task. Power factor values of 0.8 and up are considered acceptable.

PROCEDURE

1. Wire the circuit shown in Figure 6.

   In this circuit, the internal resistance of the 50 mH inductor is so small (68 ohms) compared to the 1 K, that it can be ignored. Thus, L will be considered to be a pure inductance with no R.

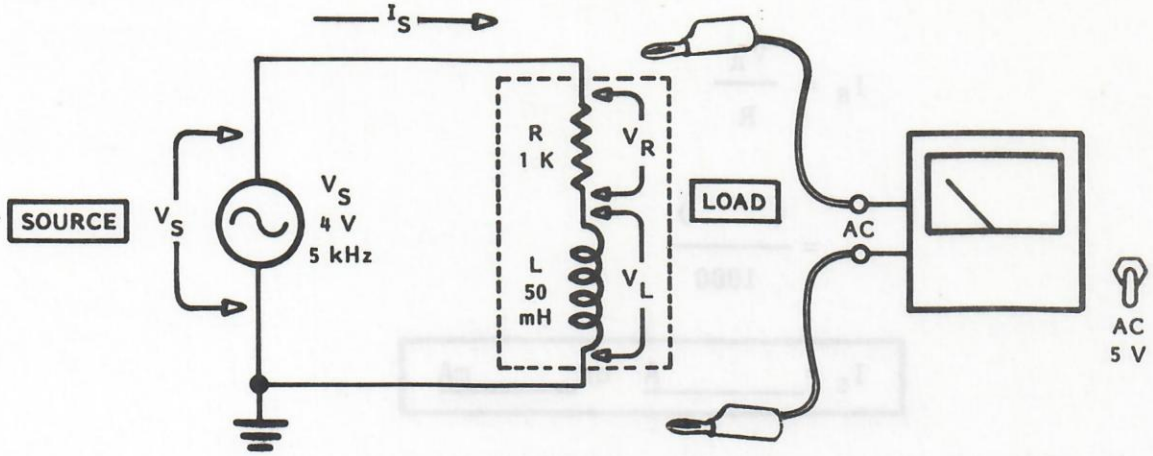


Figure 6 - Ac measurements to calculate PF; EXPERIMENT.

2. Set the Function Generator frequency to 5 kHz.

   Connect the meter across V_S and adjust the input level to 4 volts.

15.1 POWER CALCULATIONS

3. Measure V_S, V_R and V_L using the ac voltmeter set on the 5 volt range.

   Enter all the readings in Table 1.

V_S	4 V	← PRESET
V_R	V	
V_L	V	

TABLE 1 - Voltage distribution in Figure 5.

4. Calculate the input current, I_S, from:

$$I_S = \frac{V_R}{R}$$

$$= \frac{(\quad)}{1000}$$

I_S = _____ A or _____ mA

5. Calculate the input or "apparent" total power, $P_{APPARENT}$, from:

$$P_{APP} = V_S\ I_S \text{ (in mA)}$$

$$= (4)(\quad)$$

TOTAL APPARENT INPUT POWER	P_{APP} = _____ mVA

6. Calculate the true or "real" power, P_{TRUE}. This power is dissipated by the 1 K resistance and is calculated from:

$$P_{TRUE} = V_R\ I_S \text{ (in mA)}$$

$$= (\quad)(\quad)$$

TRUE OR REAL POWER	P_{TRUE} = _____ mW

15.2 POWER FACTOR CALCULATIONS

7. Calculate the power factor, PF, using the data from steps 5 and 6.

$$PF = \frac{P_{TRUE}}{P_{APP}}$$

$$= \frac{(\quad)}{(\quad)}$$

( ) ← From Step 6

( ) ← From Step 5

POWER FACTOR	PF = _____

8. Calculate the theoretical power factor from:

$$PF = \frac{R}{Z}$$

Where:

$$Z = \sqrt{R^2 + X_L^2}$$

and:

$$X_L = 2\pi fL$$

$$= (6.28)(5 \times 10^3)(50 \times 10^{-3})$$

X_L = _____ Ω

$$Z = \sqrt{1000^2 + (\quad)^2}$$

Z = _____ Ω

Given the above, the power factor is:

$$PF = \frac{R}{Z}$$

$$= \frac{1000}{(\quad)}$$

PF = _____

The power factor calculated above will differ slightly from the earlier calculation based on measurements because the actual impedance is slightly different due to the internal resistance of the inductor.

15.3 CALCULATING THETA (θ)

9. Calculate the phase angle, θ, for the circuit of Figure 6 from:

$$\theta = \text{arc cos } \frac{R}{Z}$$

$$= \text{arc cos } \frac{(1000)}{(\quad)} \leftarrow \text{From Step 8}$$

θ = _____ °

10. When the phase angle of circuit is known, it is possible to determine the power factor from:

$$PF = \cos \theta$$

Calculate the PF based on θ calculated in step 9.

$$PF = \cos (\quad °)$$

PF = _____

This PF calculation should agree with the calculation made in step 8 which was also based on the impedance, Z.

15.4 POWER FACTOR CORRECTION (OPTIONAL)

This part of the experiment requires the use of the CES 306 Power Transformer Module plug-in card as part of the load.

11. Plug the CES 306 Transformer card into the PC socket on the Ed-Lab trainer panel.

The total load in a circuit usually consists of components such as inductors, transformers and motors where the inductance and resistance are combined. We will use a series resistance to permit the measurement of the input current.

Wire the circuit shown in Figure 7.

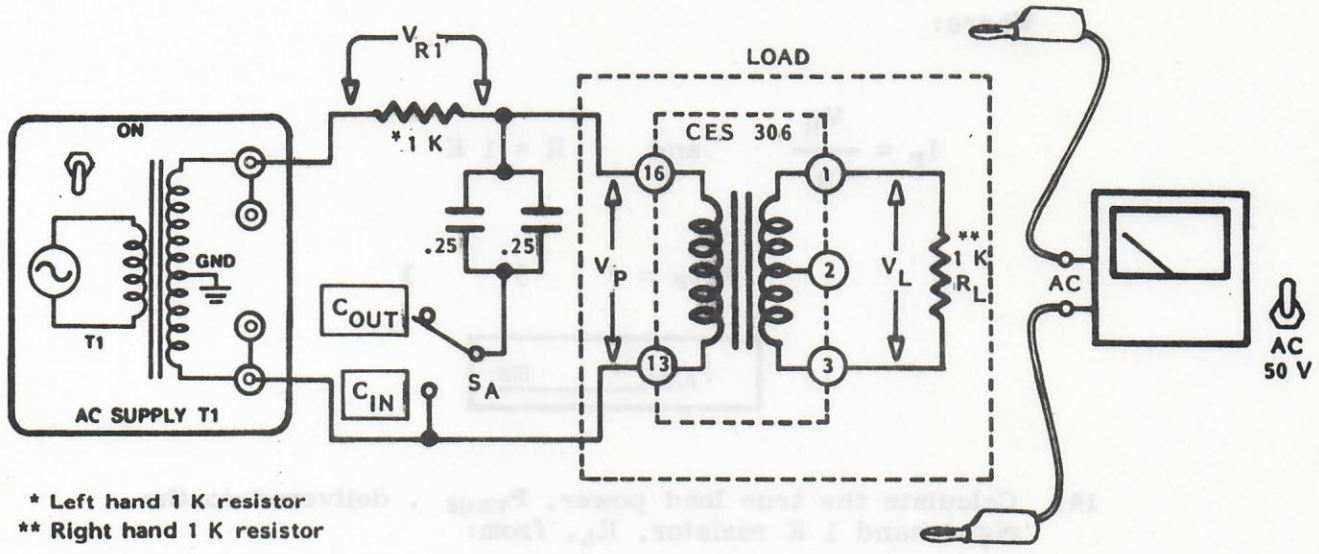


Figure 7 - Power factor correction: EXPERIMENT.

The two parallel 0.25 μF capacitors form a 0.5 μF power factor (PF) correction capacitor which is placed in the circuit when SA is set DOWN.

12. Set Switch SA UP to remove the PF correction capacitor from the circuit.

Measure the voltages V_{R1}, V_P (applied voltage), V_{RL} (load voltage) and enter the readings in Table 2.

V_{R1}	V	(Left 1 K Resistor)
V_P	V	
V_{RL}	V	(Right 1 K Resistor)

TABLE 2 - Voltage distribution in Figure 7 with SA open.

13. Calculate P_{APP} , the input power from your measurements using:

$$P_{APP} = V_P \, I_P$$

Where:

$$I_P = \frac{V_R}{R} \qquad \text{and} \qquad R = 1 \text{ K}$$

$$P_{APP} = (\quad)(\quad)$$

P_{APP}= _____ mW

14. Calculate the true load power, P_{TRUE} , delivered to the right hand 1 K resistor, R_L, from:

$$P_{TRUE} = \frac{V_{RL}^2}{R_L}$$

$$= \frac{(\quad)^2}{1000}$$

P_{TRUE}= _____ mW

15. Calculate the power factor from:

$$PF = \frac{P_{TRUE}}{P_{APP}}$$

$$= \frac{(\quad)}{(\quad)} \begin{array}{l} \leftarrow \text{From Step 14} \\ \leftarrow \text{From Step 13} \end{array}$$

PF = _____

How much power is lost in the transformer?

P_{LOST} = _____ mW

CAPACITOR ADDITION FOR CORRECTION

16. Place Switch SA DOWN to add the PF correction capacitor into the circuit.

Measure V_{R1}, V_P, V_{RL} and enter the readings in Table 3.

V_{R1}	V
V_P	V
V_{RL}	V

TABLE 3 - Voltage distribution in Figure 7 with SA closed.

17. Calculate the true and apparent powers.

$$P_{TRUE} = \frac{V_{RL}^2}{R_L}$$

$$= \frac{(\quad)^2}{1000}$$

P_{TRUE} = _____ mW

$$P_{APP} = V_P \, I_P$$

$$= (\quad)(\quad)$$

P_{APP}= _____ mW

How does the true power in the compensated circuit compare to the true power from step 14 (uncompensated)?

_____

_____

How does the apparent power in the compensated circuit compare to the apparent power from step 13 (uncompensated)?

_____

_____

_____

18. Calculate the new power factor from:

$$PF = \frac{P_{TRUE}}{P_{APP}}$$

$$= \frac{(\quad) \leftarrow \text{From Step 17}}{(\quad) \leftarrow \text{From Step 17}}$$

MEASURED CORRECTED POWER FACTOR	PF = _____

Compare this new, corrected, PF with that measured in step 16. Is the new PF closer to 1?

_____

19. In our earlier description, the apparent power, P_{APP}, was 9,600 VA, P_{TRUE} was 6,400 watts and the power factor, PF, was 0.666. If the power factor in that circuit was improved by a PF correction capacitor to 0.8, we will calculate the savings in dollars per year given that the load was used 24 hours per day, 7 days per week, 50 weeks per year. Assume a cost of 14¢ per kilowatt hour (KWH).

$$PF = \frac{P_{TRUE}}{P_{APP}}$$

$$0.666 = \frac{6,400}{9,600}$$

Given the new PF of 0.8, we have:

$$P_{APP} = \frac{P_T}{PF}$$

$$= \frac{6,400}{0.8}$$

$$P_{APP} = 8000 \text{ VA}$$

$$P_{SAVED} = P_{APP} \text{ @ } 0.666 - P_{APP} \text{ @ } 0.8$$

$$= 9,600 - 8,000$$

$$= 1,600 \text{ VA} = 1.6 \text{ kVA}$$

The new corrected power factor has reduced the apparent power by one third while leaving the true power practically unchanged. Because it is the apparent power that the utility companies bill for, the improved power factor provides a considerable savings in cost.

The saved power, 1,600 kVA, costs 14¢ per kwh. This results in a savings of $ 0.224 per hour. At 24 hours per day, 7 days per week, 50 weeks per year, the total saved is:

$$\$ \text{ SAVED} = (\$0.224)(24 \text{ hours})(7 \text{ days})(50 \text{ weeks})$$

$$\boxed{\$ \text{ SAVED} = \$1,881.60 \text{ per year}}$$

CONCLUSIONS

We have learned from this experiment that:

In a dc resistive circuit the power dissipation is equal to:

$$P = E \cdot I$$

In an ac circuit the power, at any instant of time, is equal to:

$$P_{inst} = e \cdot i$$

Pure capacitors and inductors consume no power.

In an ac resistive circuit, the power is equal to:

$$P = E_{rms} \cdot I_{rms}$$

In a resistive-reactive circuit, only the resistance dissipates true power which is calculated from:

$$P_{TRUE} = I^2 R$$

The apparent power of a resistive-reactive circuit, P_{APP}, is calculated from the source voltage and the measured current drain as:

$$P_{APP} = E_S \cdot I_{LOAD}$$

The unit for "apparent" power is the VOLT AMPERE, VA, not the WATT which refers to "true" power.

In a resistive-reactive power circuit the apparent power is always greater than the true power.

The Power Factor, PF, is equal to the ratio of the true power to the apparent power:

$$PF = \frac{P_{TRUE}}{P_{APP}}$$

Power factor ranges from 1, the best, to 0, the poorest.

A lagging PF (inductive) can be compensated for by the addition of the correct amount of capacitance.

The correction capacitor leaves the true power unchanged while it reduces the apparent power.

The power factor can be calculated from:

$$PF = \frac{P_{TRUE}}{P_{APP}} \qquad PF = \frac{R}{Z} \qquad PF = \cos \theta$$

An improved power factor results in a reduced utility power bill.

ASSIGNMENT

Answer the following multiple choice questions.

1. Power in an ac circuit is the same as power in a dc circuit when the ac load is:

   a. inductive.
   b. capacitive.
   c. resistive.
   d. all of the above.

2. When in an ac circuit, a capacitor:

   a. stores energy.
   b. returns energy to the circuit.
   c. consumes no power.
   d. all of the above.

3. With an ac resistive-reactive load, the power that has to be paid for is:

   a. only that power dissipated by the resistance.
   b. only that power dissipated by the reactance.
   c. the apparent power.
   d. the true power.

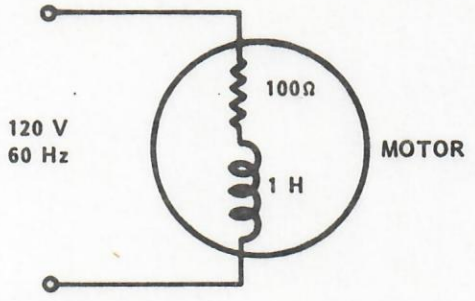


Figure 9 refers to questions 4 to 10.

4. The inductive reactance of the motor in Figure 4 is closest to:

   a. 377 ohms.
   b. 188 ohms.
   c. 60 ohms.
   d. none of the above.

5. The impedance of the motor in Figure 9 is closest to:

   a. 376 ohms.
   b. 390 ohms.
   c. 408 ohms.
   d. none of the above.

6. The current drained by the motor in Figure 9 is closest to:

   a. 0.3 A.
   b. 30 mA.
   c. 0.03 x PF.
   d. none of the above.

7. The apparent power dissipated by the motor in Figure 9 is closest to:

   a. 3.6 VA.
   b. 21 VA.
   c. 37 VA.
   d. 37 W.

8. The true power for the motor in Figure 9, is:

   a. 3.6 W.
   b. 9.5 W.
   c. 21 W.
   d. 37 W.

9. The motor in Figure 9 has a Power Factor closest to:

   a. 0.87.
   b. 0.54.
   c. 0.37.
   d. 0.26.

10. Adding a correct value capacitor across the motor in Figure 9, will result in:

   a. lowering the power factor.
   b. decreasing the true power dissipation.
   c. decreasing the apparent power dissipation.
   d. all of the above.

KEY TERMS

1. APPARENT POWER

   The product of the E · I in an ac circuit when the voltage and current are out of phase. The unit for apparent power is volt-amperes.

2. POWER

   The energy dissipated in an electrical circuit in the form of heat.

3. POWER FACTOR

   The ratio of true power to the apparent power in an ac reactive circuit. The power factor, PF, has a value between 0 and 1.

4. TRUE POWER

   The power dissipated by the resistive portion of an RL or RC circuit.

5. VOLT-AMPERES

   The unit for apparent power, calculated from the source voltage, V, and the line current in amperes, A.

Lissajous Patterns 16

OBJECTIVES

When you finish this experiment you will be able to:

1. List three methods of measuring frequency.
2. Measure the phase difference between two signals using Lissajous Patterns.
3. Measure the frequency of a signal by using Lissajous Patterns.
4. Check the calibration of a Function Generator using Lissajous Patterns.
5. Plot the calibration check on two cycle log-log graph paper.

DESCRIPTION

The frequency of an ac signal can be measured using one of several methods. There is the direct reading digital Frequency Counter in which the exact frequency is read from the digital display as shown in Figure 1. Some digital frequency meters read as high as 400 mHz and higher.

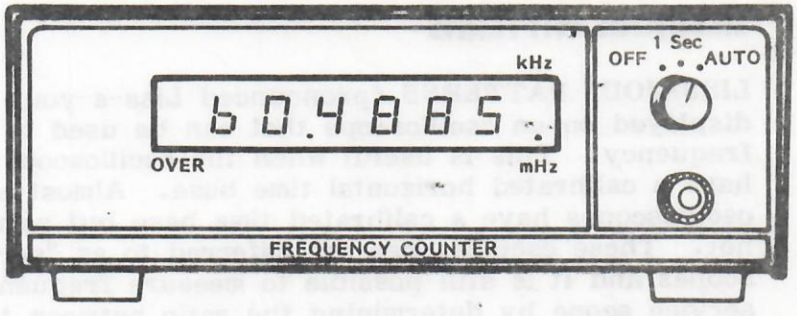


Figure 1 - Panel view of a digital frequency counter.

A second method of determining the frequency of an ac voltage is to measure the period of one cycle of the waveform using an oscilloscope. When the period, T, is known, the frequency can be calculated from:

$$f = \frac{1}{T}$$

For example, if the time base of one complete cycle on the crt display measures 5 cm and the TIME/CM control is set at 2 mS, then:

$$f = \frac{1}{T} = \frac{1}{(5)(2\ \text{mS})}$$

$$= \frac{1}{(5)(2 \times 10^{-3})} = \frac{1000}{10}$$

$$\boxed{f = 100\ \text{Hz}}$$

LISSAJOUS PATTERNS

LISSAJOUS PATTERNS (pronounced Liss-a-you) are pictures displayed on an oscilloscope that can be used to measure frequency. This is useful when the oscilloscope does not have a calibrated horizontal time base. Almost all modern oscilloscopes have a calibrated time base but some few do not. These oscilloscopes are referred to as "service" scopes and it is still possible to measure frequency using a service scope by determining the ratio between the frequency of the signal being tested and a known reference frequency.

The two frequencies are applied to the X and Y inputs of the service oscilloscope to produce the patterns as shown in Figure 2.

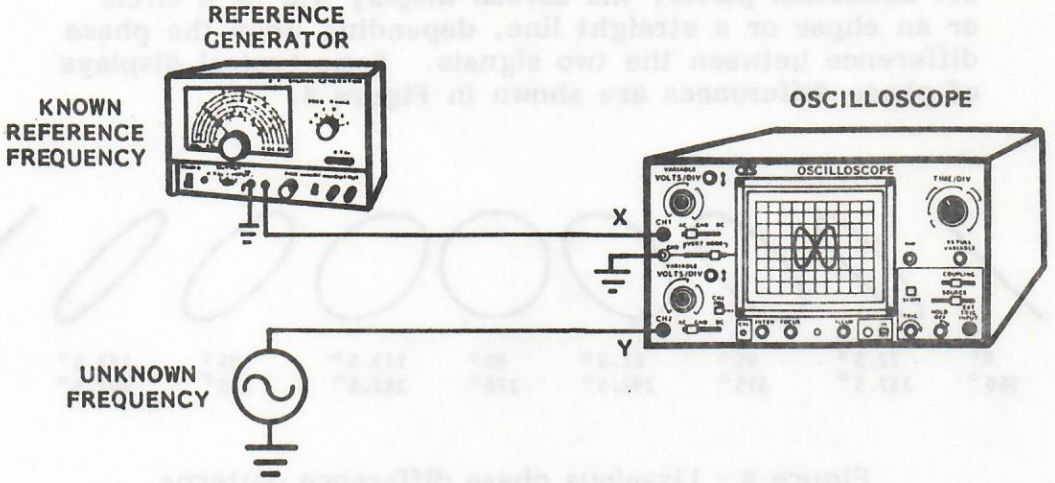


Figure 2 - Checking frequency using Lissajous Patterns.

In addition to measuring frequency using Lissajous Patterns, it is possible to measure the Phase Difference between two signals of the same frequency. A typical arrangement is shown in Figure 3.

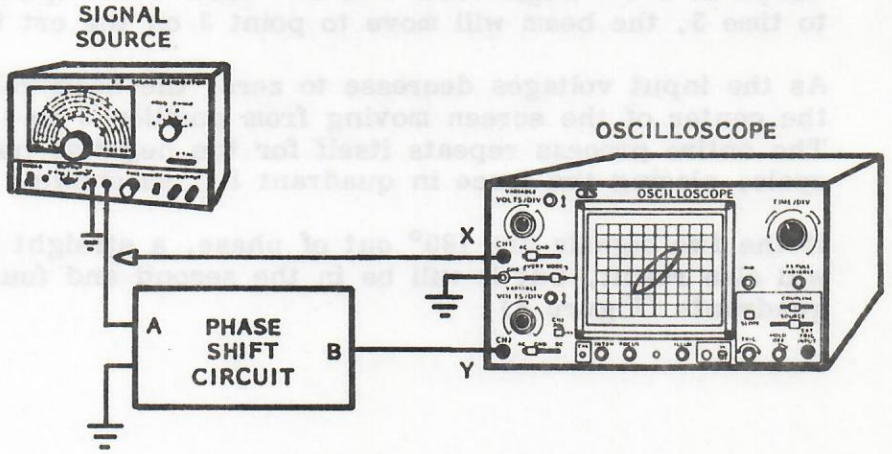


Figure 3 - Phase difference measurement using Lissajous Patterns.

PHASE MEASUREMENTS

When two signals of the same frequency are applied to the crt deflection plates, the screen display will be a circle or an elipse or a straight line, depending upon the phase difference between the two signals. Some typical displays of phase differences are shown in Figure 4.

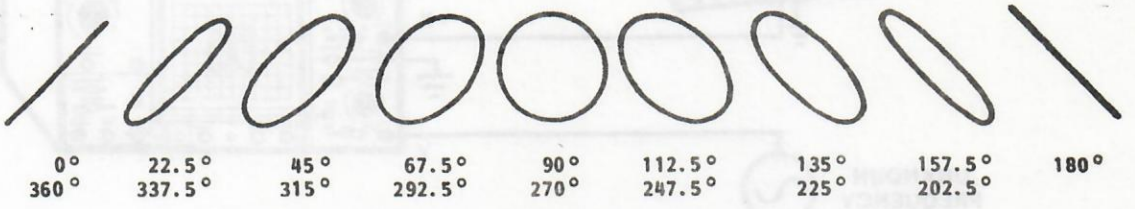


Figure 4 - Lissajous phase difference patterns.

As shown in Figure 4, when both sine waves applied to the deflection plates are the same frequency, in phase, and the same amplitude, the result is a straight line at a 45° angle. Figure 5 illustrates how a Lissajous pattern is formed. When both inputs are at time 1, the electron beam is resting at dead center, 1, on the crt screen.

As both sine waves advance to time 2, the beam is moved upwards towards A and sideways towards B. The vector resultant places the beam at point 2 and the beam will have moved at a 45° angle from 1 to 2. When both inputs advance to time 3, the beam will move to point 3 on the crt face.

As the input voltages decrease to zero, the beam returns to the center of the screen moving from position 3 to 4 to 5. The entire process repeats itself for the negative half cycle, placing the trace in quadrant III, as shown.

If the two signals are 180° out of phase, a straight line will also result, but it will be in the second and fourth quadrants (Figure 4).

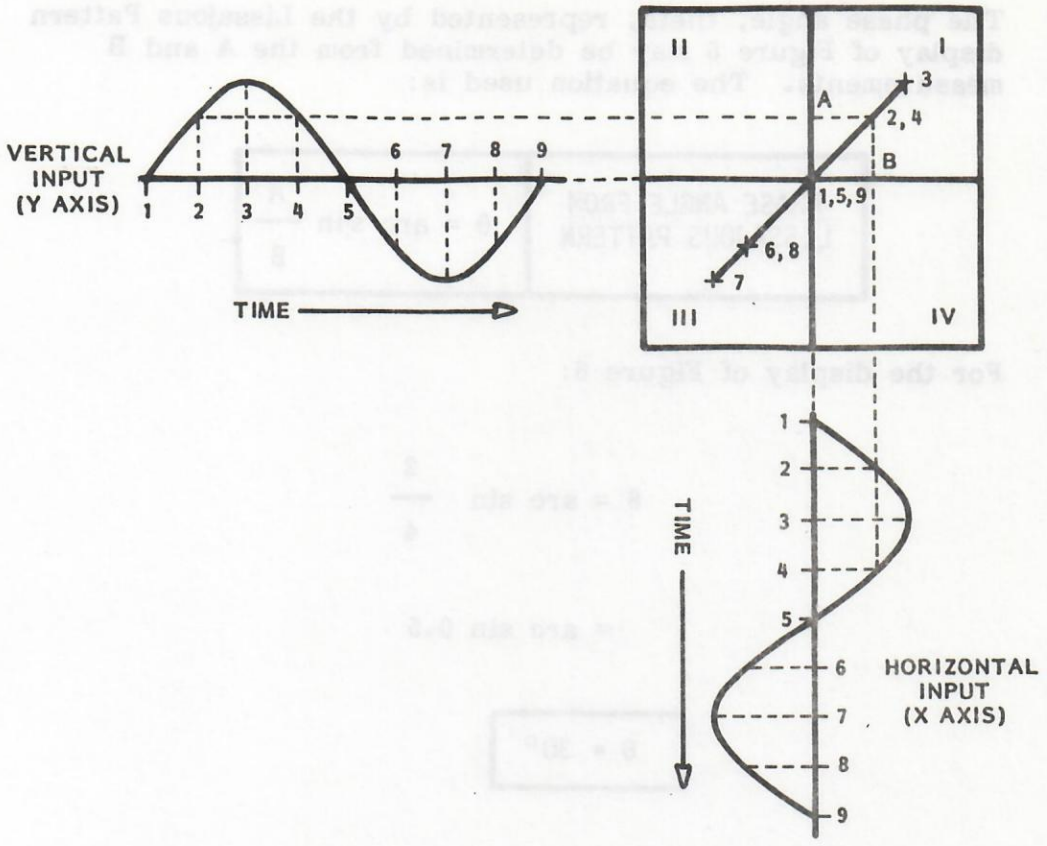


Figure 5 - Lissajous pattern resulting from two in-phase signals.

CALCULATING THE PHASE ANGLE

To measure the phase angle between two signals, it is necessary that the resulting pattern be positioned approximately in the center of the crt screen as shown in Figure 6. Adjust the X and Y channel gain controls for a reasonably sized display.

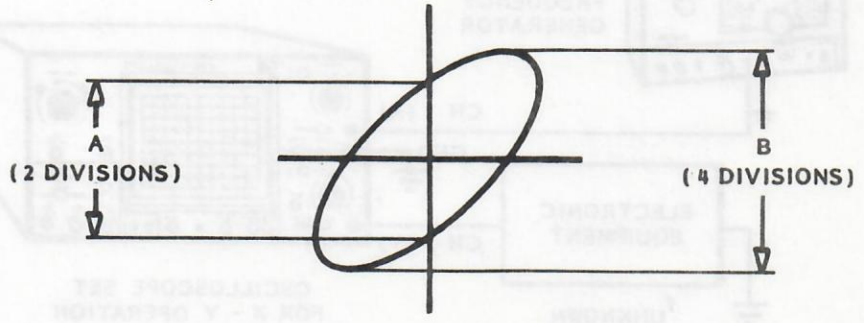


Figure 6 - Pattern measurement points to determine Theta.

The phase angle, theta, represented by the Lissajous Pattern display of Figure 6 may be determined from the A and B measurements. The equation used is:

PHASE ANGLE FROM LISSAJOUS PATTERN	$\theta = \arcsin \frac{A}{B}$

For the display of Figure 6:

$$\theta = \arcsin \frac{2}{4}$$

$$= \arcsin 0.5$$

$$\theta = 30°$$

FREQUENCY MEASUREMENT

When the sine waves applied to each deflection plate are of different frequencies, a different set of Lissajous Patterns will appear than those previously discussed. The equipment set-up needed to measure frequency or phase using Lissajous Patterns is shown in Figure 7.

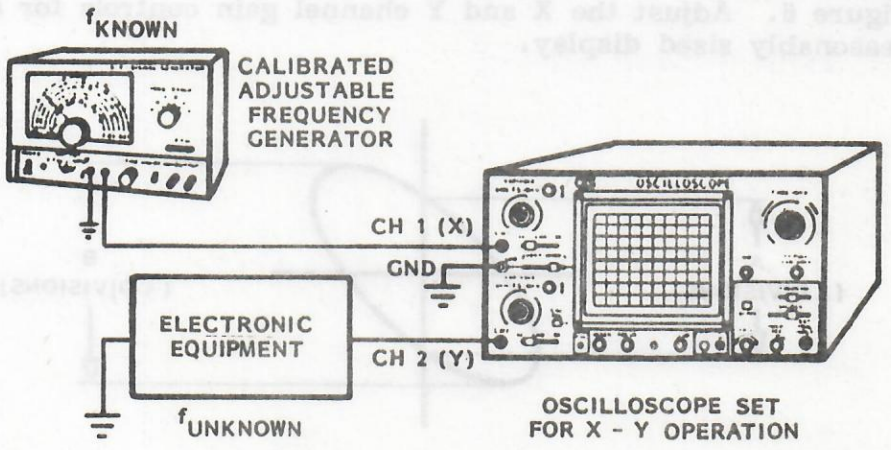


Figure 7 - Lissajous pattern test set-up with triggered scope.

As shown in Figure 7, the known signal is applied to one axis (typically the X axis) and the unknown signal is applied to the other axis (Y). When the unknown frequency is twice the known frequency, the resulting screen display will be that shown in Figures 8 and 9.

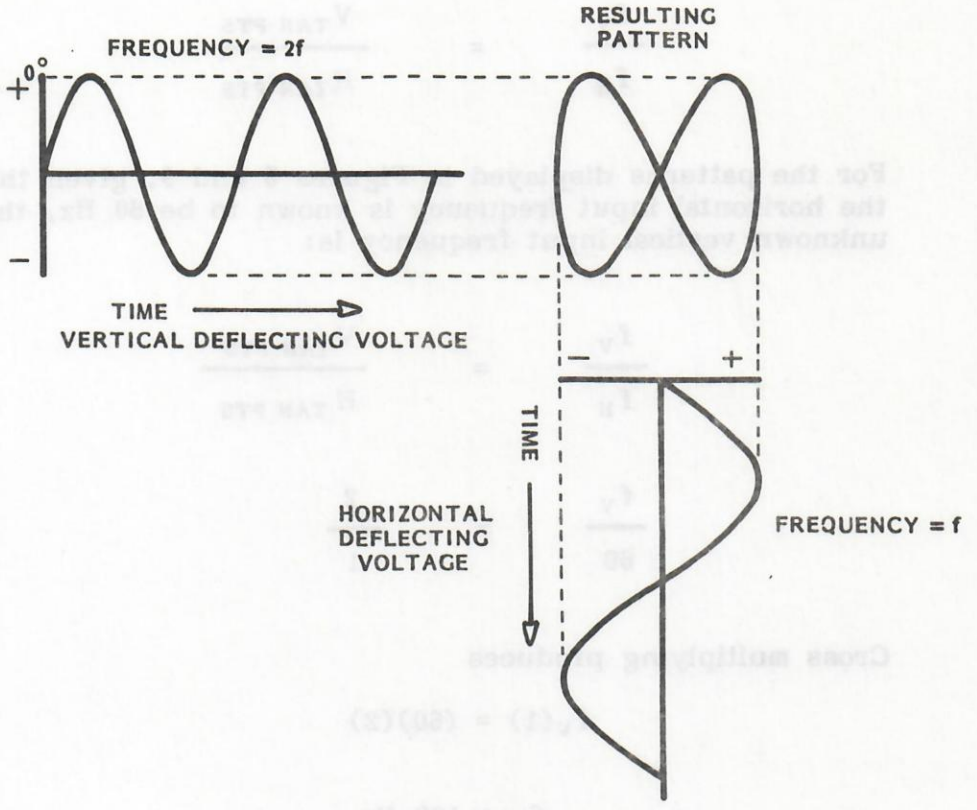


Figure 8 - Screen display for a 2:1 Lissajous Pattern.

By counting the horizontal tangent point, A (1 point) in Figure 9 and the vertical tangent points, B (2 points), also in Figure 9, it is possible to determine the frequency of the unknown signal. This shows that the Y frequency is twice the X frequency.

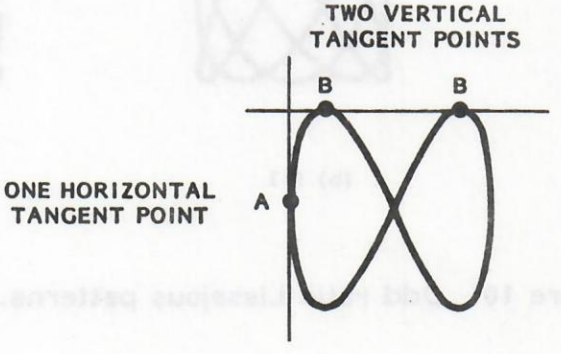


Figure 9 - Tangent point count on a 2:1 display.

The ratio of the horizontal and vertical tangent points is a function of the two frequencies and is expressed as:

$$\frac{f_V}{f_H} = \frac{V_{TAN\ PTS}}{H_{TAN\ PTS}}$$

For the patterns displayed in Figures 8 and 9, given that the horizontal input frequency is known to be 60 Hz, the unknown vertical input frequency is:

$$\frac{f_V}{f_H} = \frac{V_{TAN\ PTS}}{H_{TAN\ PTS}}$$

$$\frac{f_V}{60} = \frac{2}{1}$$

Cross multiplying produces

$$f_V(1) = (60)(2)$$

$$f_V = 120\ Hz$$

A 3:1 (read as 3 to 1) Lissajous Pattern is shown in Figure 10(a) which indicates that the unknown vertical frequency is 3 times the known horizontal signal frequency.

(a) 3:1 (b) 5:3 (c) 5:4

Figure 10 - Odd ratio Lissajous patterns.

This type of pattern can be read as high as 8 or 9:1. Above 9:1, the pattern movement makes the count very difficult. Other ratios, such as 5:3 and 5:4 shown in Figure 10(b) and (c), may also be used. For example, if a 60 Hz X axis input and an unknown Y axis input produce the 5:4 display of Figure 10(c), then f_V is:

$$\frac{f_V}{f_H} = \frac{V_{TAN\ PTS}}{H_{TAN\ PTS}}$$

$$\frac{f_V}{60} = \frac{5}{4}$$

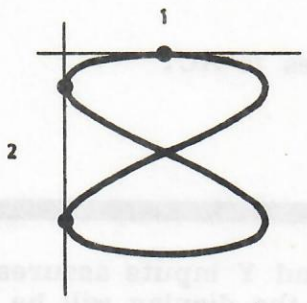
Cross multiplying produces

$$f_V(4) = (60)(5)$$

$$f_V = \frac{300}{4}$$

$$\boxed{f_V = 75\ \text{Hz}}$$

When the unknown vertical (Y) frequency is lower than the known horizontal (X) frequency, the pattern flips over as shown in Figure 11. A 1:2 ratio is shown along with the mathematical solution for a known 60 Hz horizontal signal.



1:2 PATTERN

$$\frac{f_V}{f_H} = \frac{V_{TAN\ PTS}}{H_{TAN\ PTS}} = \frac{f_V}{60} = \frac{1}{2}$$

$$2f_V = 60$$

$$f_V = \frac{60}{2}$$

$$\boxed{f_V = 30\ \text{Hz}}$$

Figure 11 – a 1:2 ratio pattern and a typical solution.

PROCEDURE

16.1 EQUIPMENT SET-UP

1. Wire the circuit shown in Figure 12.

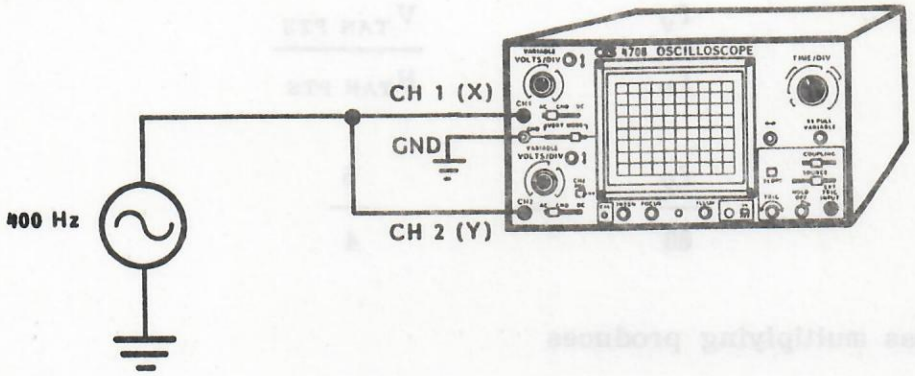


Figure 12 - Phase measurement EXPERIMENT.

2. Set the Function Generator to 400 Hz at maximum output.

3. Set the oscilloscope to the X-Y function (TIME/DIV switch fully ccw).

   Set the CH 1 and CH 2 vertical controls to 2V/DIV and make sure the variable controls are all in the CALIBRATE position.

   Set the input switches to GND.

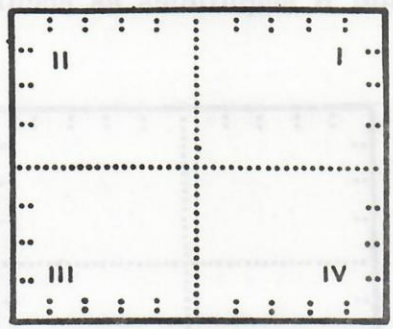
   Adjust the centering controls so that the beam strikes the center of the screen where the X and Y calibration lines cross.

   Set the CH 1 and CH 2 Input Switches to AC.

16.2 CHECKING THE OSCILLOSCOPE

4. Feeding the same signal into the X and Y inputs assures a 0° degree phase difference so that the display will be a solid line running through quadrants I and III.

Draw the display in the space provided below:



5. If there is a slight elipse instead of a straight line, it means that one of the two amplifiers (the V or H) has a small phase shift.

   If the line lies in the II and IV quadrants, there is a 180° phase difference between the V and H amplifiers. Check to see if the CH 2 INVERT switch is in the correct position (out).

16.3 MEASURING RC PHASE SHIFT

6. Wire the circuit shown in Figure 13.

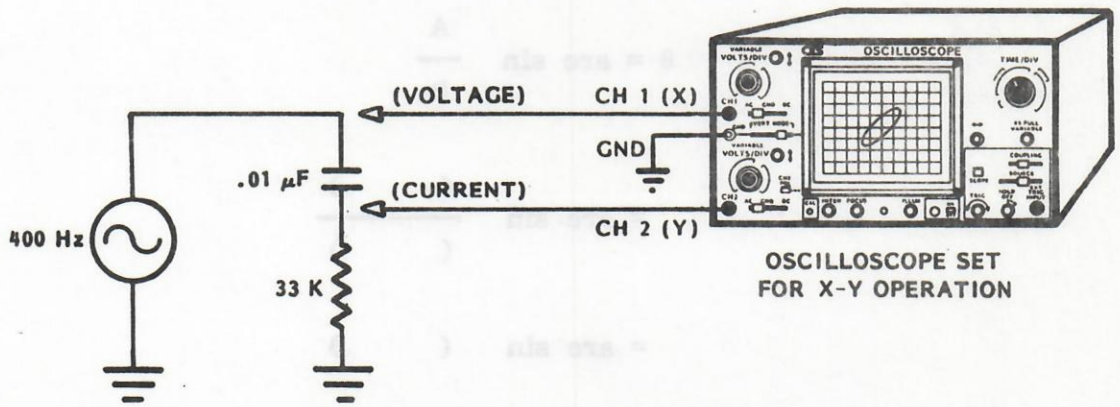
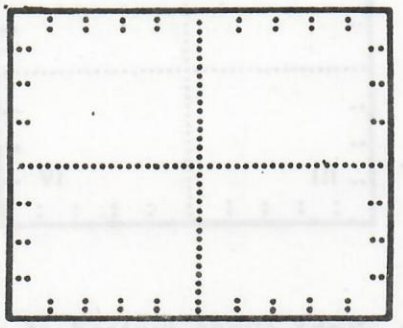


Figure 13 - RC phase shift measurement; EXPERIMENT.

Use the oscilloscope control setting from step 3 and be certain the centering is still correct.

7. Draw the screen display in the space provided below and mark the A and B amplitudes as accurately as possible.



8. Record the A and B amplitude measurements below.

A = _____	DIVISIONS
B = _____	DIVISIONS

9. Calculate the phase angle, theta, using the data from step 8.

$$\theta = \text{arc sin } \frac{A}{B}$$

$$= \text{arc sin } \frac{(\quad)}{(\quad)}$$

$$= \text{arc sin } (\quad)$$

MEASURED PHASE ANGLE	θ = _____ DEGREES

10. Calculate the theoretical phase angle using the capacitive reactance of the 0.01 capacitor at 400 Hz and the resistance of 33 K.

$$X_C = \frac{1}{2\pi fc} = \frac{1}{(6.28)(400)(0.01 \times 10^{-6})}$$

$$= \frac{10^6}{25.12}$$

X_C = 39,809 OHMS

$$\theta = \text{arc tan } \frac{X_C}{R}$$

$$= \text{arc tan } \frac{39,809}{33,000}$$

$$= \text{arc tan } (\quad)$$

CALCULATED PHASE ANGLE	θ = _____ DEGREES

How do the measured and theoretical phase angles compare?

_____

_____

16.4 LISSAJOUS FREQUENCY MEASUREMENT

11. Remove the existing wiring and assemble the circuit shown in Figure 14.

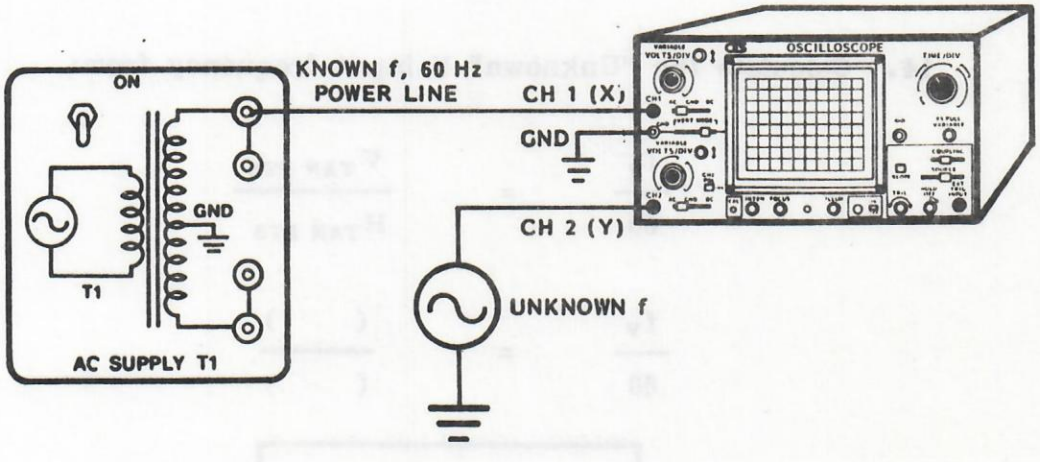


Figure 14 - Circuit for measuring frequency; EXPERIMENT.

Observe that, in Figure 14, the known frequency fed to the X axis is from the 60 Hz power line. This frequency is very accurately maintained by the power companies and is extremely dependable. All Y input frequencies will be tested against the 60 Hz power line signal.

12. Set the CH 1 (X) V/DIV switch at 5V.

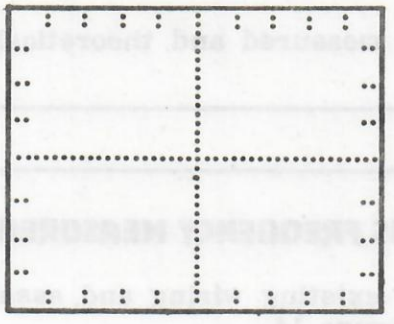
    Set the CH 2 (Y) V/DIV switch at 2V.

    Set the Function Generator to 60 Hz, maximum output.

    Observe the display. You may have to adjust the generator frequency in order to show a 1:1 frequency ratio with a constant phase shift from 0° to 180° back to 0° (360°) again. The rotation in phase will be constant because the Function Generator frequency is constantly shifting phase.

13. Set the Function Generator to 30 Hz and adjust the frequency control for as steady a pattern as possible.

    Draw the pattern in the space provided below.



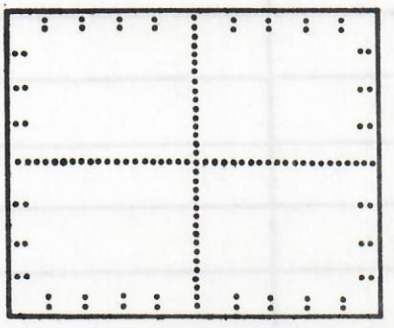
14. Calculate the "Unknown" Y input frequency from:

$$\frac{f_V}{60} = \frac{V_{TAN\ PTS}}{H_{TAN\ PTS}}$$

$$\frac{f_V}{60} = \frac{(\quad)}{(\quad)}$$

$f_V =$ _____ Hz

15. Set the Function Generator frequency to 90 Hz and draw the pattern in the space provided below.



Calculate the unknown input frequency from:

$$\frac{f_V}{60} = \frac{V_{TAN\ PTS}}{H_{TAN\ PTS}}$$

$$\frac{f_V}{60} = \frac{(\ )}{(\ )}$$

$$(\ )f_V = (\quad)(\quad)$$

$f_V =$ _____ Hz

16.5 GENERATOR CALIBRATION CHECK (OPTIONAL)

16. The frequency calibration of any generator can be checked over a portion of its range using the 60 Hz power line as the known reference frequency.

Using the circuit of Figure 13 still wired on the panel, set the Function Generator to each of the frequencies listed in Table 1.

Adjust the frequency knob so that the required Lissajous pattern appears on the crt and record the precise frequency control setting.

TEST FREQUENCY (Hz)	GENERATOR DIAL SETTING (Hz)	PATTERN RATIO
30		1:2
60		1:1
90		3:2
120		2:1
180		3:1
240		4:1
300		5:1
360		6:1
420		7:1
480		8:1

TABLE 1 - Generator dial readings versus 60 Hz.

17. Plot the results of Table 1 on the 2 cycle log-log graph in Figure 15 and connect the dots with a straight edge.

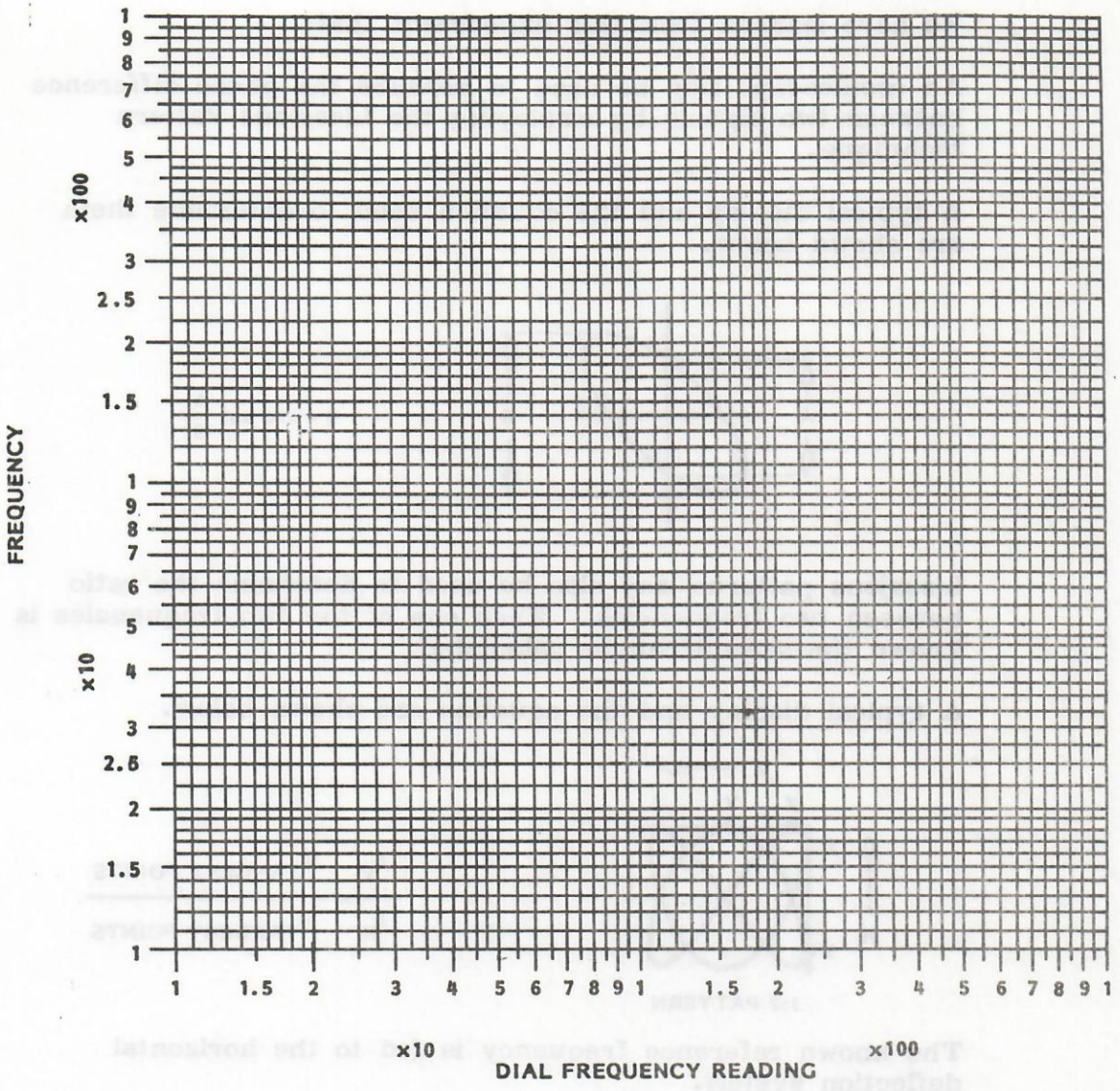


Figure 15 - Plot of Function Generator dial readings versus actual frequency.

Is the Function Generator dial calibration accurate over the range measured?

_____

_____

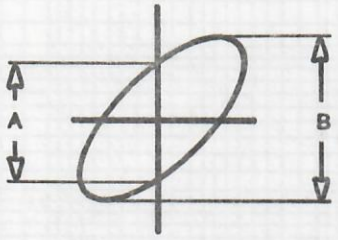
_____

CONCLUSIONS

We have learned from this experiment that:

An oscilloscope may be used to measure the phase difference between two signals by employing the Lissajous Pattern technique.

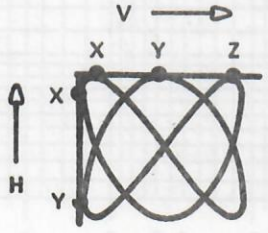
A typical display and the equation used to determine theta are shown below.



$$\theta = \arcsin \frac{A}{B}$$

Lissajous patterns may also be used to determine the ratio between two frequencies. When one of the two frequencies is known the second can be calculated.

A typical display and the equation are shown below.

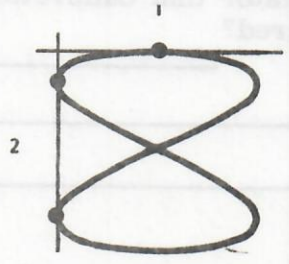


3:2 PATTERN

$$\frac{f_V}{f_H} = \frac{V_{\text{TANGENT POINTS}}}{H_{\text{TANGENT POINTS}}}$$

The known reference frequency is fed to the horizontal deflection system.

When the unknown frequency, fed to the vertical deflection system, is lower than the known frequency, the Lissajous pattern will have, as shown below, more horizontal tangent points than vertical.



1:2 RATIO

A plot of frequency versus frequency is best made on log-log graph paper.

ASSIGNMENT

Answer the following multiple choice questions.

1. Two full cycles of a signal cover 5 cm, horizontally, on an oscilloscope screen. If the V/CM control is set at 2 and the TIME/CM control at 50 microseconds, the frequency of the displayed signal is:

   a. 4 kHz.
   b. 8 kHz.
   c. 10 kHz.
   d. 20 kHz.

2. The phase difference between two signals can be measured using a _____ or a _____.

   a. dual trace oscilloscope, Lissajous Pattern.
   b. dual trace oscilloscope; Frequency Counter.
   c. digital multimeter, dual trace oscilloscope.
   d. Lissajous Pattern; Frequency Counter.

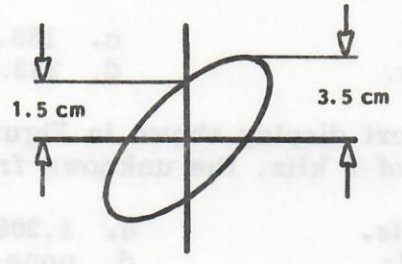


Figure 16 above refers to question 3.

3. The Lissajou pattern in Figure 16 indicates a phase relationship between two signals of:

   a. 23.19°
   b. 25.37°
   c. 64.62°
   d. 66.8°

4. A Lissajous Pattern display of a perfect circle indicates a:

   a. 90° phase difference.
   b. 1:1 frequency ratio.
   c. both a and b.
   d. neither a nor b.

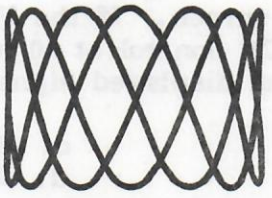


Figure 17 refers to questions 5 and 6.

5. Given the crt display shown in Figure 17 and a horizontal frequency of 200 Hz, the unknown frequency is closest to:

   a. 40 Hz.
   b. 66.6 Hz.
   c. 166.65 Hz.
   d. 333.33 Hz.

6. Given the crt display shown in Figure 17 and a vertical frequency of 2 kHz, the unknown frequency is closest to:

   a. 3,333 Hz.
   b. 1,500 Hz.
   c. 1,200 Hz.
   d. none of the above.

KEY TERMS

1. CALIBRATION

   The comparison of the accuracy of the scale markings of an instrument against a known standard.

2. LISSAJOU PATTERN

   Patterns displayed on the crt screen, in the X-Y mode, when voltages of different phases and frequencies are applied to the vertical and horizontal inputs at the same time.

3. LOG-LOG GRAPH PAPER

   Graph paper on which both the X and Y axis are calibrated with a logarithmic scale instead of a linear scale.

4. PHASE ANGLE (θ)

   The angular differences, measured in degrees, between two electrical waveforms in an ac circuit.

5. PHASE DIFFERENCE

   The time, measured in degrees, that one electrical waveform leads or lags another waveform of the same frequency.

6. PHASE SHIFT

   The difference, in degrees, between the input signal and the output signal.

7. RC PHASE SHIFT

   The phase shift caused by the capacitive reactance portion of an RC circuit.

8. TANGENT POINT

   The point at which a straight line touches the circumference of a circular or elipse at one point.

Troubleshooting AC Circuits 17

OBJECTIVES

When you finish this experiment you will be able to:

1. Wire the circuit of a system that performs the specific functions of Mixing and Separating.
2. Determine if the wired system is functioning correctly.
3. Signal trace through the system to locate the faulty stage.
4. Perform a resistance and voltage analysis to locate the defective component.
5. Use the provided Service Information data to aid in locating the faults.

ADDITIONAL EQUIPMENT REQUIRED

DVOM or FETVOM

DESCRIPTION

All the experiments in this ac unit, G3, involved circuits that were, individually, very simple. If, in the process of assembling these circuits, an error was made, the error was relatively easy to find by examining the circuit wiring or making simple measurements and tests. The faults which were inserted by the instructor were also isolated by simple tests. As circuits become more complex, however, finding faults by visual inspection or random tests becomes more difficult. You will have some troubleshooting experience, if, in any of the previous experiments, your instructor introduced faults for you to locate. This experience will help you in this experiment.

The block diagram in Figure 1 consists of several different circuits which have been studied in this unit, interconnected in a "System" to perform a "Function." Three signals are mixed, processed and then separated at the output. The mixing process is called MULTIPLEXING and the process of separating the signals again, is called DEMULTIPLEXING.

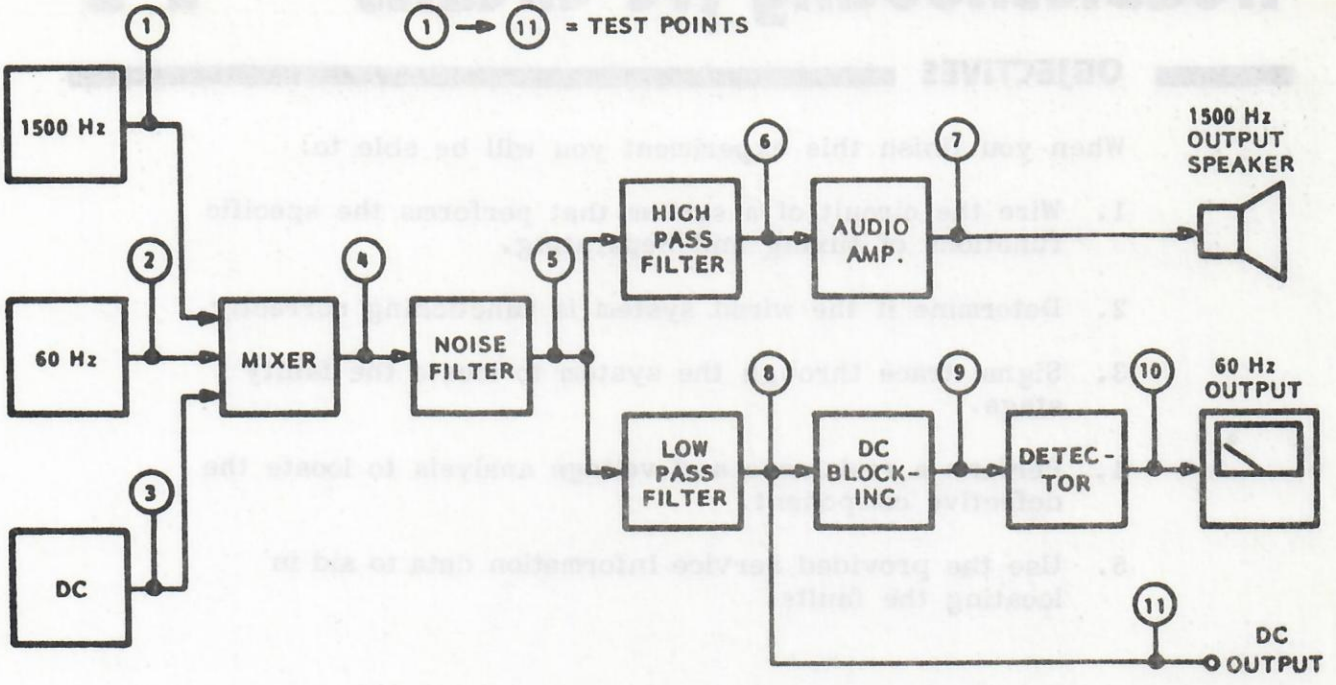


Figure 1 - Block diagram of the system to be wired for troubleshooting practice.

The three "signals," 60 Hz, 1500 Hz and a dc level, are fed into the Mixer stage. The output of the mixer is then fed to a Noise Filter which is a low pass filter with an f_c of 72.4 kHz. Any signals above 72.4 kHz are assumed to be pick-up from external sources, are classified as unwanted noise and are attenuated (removed). The output from the Noise Filter is then fed to the High Pass and Low Pass filters that separate the 60 Hz and 1500 Hz signals. The 1500 Hz signal represents the audio set of frequencies for voice transmission. The 60 Hz signal represents a slow speed code transmission. Both signals are "multiplexed" over a single line. In a television system, the audio signal, the video signal and several other signals are all combined in one transmission.

The 1500 Hz signal, processed by the High Pass filter, is fed to the Op-Amp Audio Amplifier. The Op-Amp amplifies the signal and drives the speaker. The 60 Hz signal, processed by the Low Pass filter, is fed to a Detector stage through the DC Blocking stage which consists of a 5 μF capacitor. The function of the capacitor is to block dc which is either another signal (as in this instance) or an unwanted voltage offset from previous circuits. The desired dc output is taken just before the 5 μF blocking capacitor at Test Point (TP) 11. The 60 Hz signal, fed to the Detector stage is converted to dc (detected) and read on the meter.

TROUBLESHOOTING PROCEDURE

To locate faults in a circuit, it is necessary to understand the circuit "signal flow." This consists of knowing the input signals, their path in the circuit and the expected outputs, as well as the levels of signal at every point along the signal flow. If the troubleshooter is fortunate, Service Information manuals will be available. The manuals usually contain the circuit, the dc voltages, ac voltages and waveforms to be expected at the various test points. This data will be either in tabular form or on the schematic diagram.

The points to be tested are chosen in a logical sequence. For example, a fault occurs that causes the 1500 Hz output to fail but not the 60 Hz and dc outputs. The test points in Figure 1 that should be checked are 7, 6, 5, 4 and 1, in that order. Further testing of individual components and wires would be indicated by the results obtained.

The circuit represented by the block diagram of Figure 1 is shown in the schematic of Figure 2. The expected measurements and waveforms for normal operation are given in Table 1.

TROUBLESHOOTING METHODS

There are many troubleshooting methods. These include testing at various points for signal waveforms and voltages, using diagnostic test equipment, substitution based on symptoms, using "flow charts," and others. Two signal monitoring methods used for ac circuits are SIGNAL INJECTION and SIGNAL TRACING. Signal Injection, as the name implies, consists of the technician inserting a signal, from a test generator, to any point in the circuit, to see if it will pass through a specific circuit block under test.

The Signal Tracing method uses the original signal present, or an inserted input signal, and requires that the signal present at each test point be examined with a suitable test instrument, most frequently an oscilloscope or meter. The observed signals are compared to the data provided in the Service Information Manual. When an incorrect waveform or voltage is found, a voltage and resistance test of the affected circuit will usually indicate the actual fault.

In this experiment, you will wire the circuit of Figure 2 and run the tests listed in Table 1 for normal conditions. Your instructor will then insert faults which you will locate using the Signal Tracing procedure.

TP	DCV	ACV	WAVEFORM
1	0.866	4.36	12 v pp
2		10.26	30 v pp
3	9.00		
4	1.33	3.23	15 v pp
5	1.33	1.82	8 v pp
6	0.00	0.26	0.8 v pp
7	0.00	0.184	0.7 v pp
8	1.31	0.822	2.5 v pp
9	- 0.43	0.822	2.5 v pp
10	0.15	0.286	0.7 v pp
11	1.31	0.822	0.7 v pp

TEST CONDITIONS
1. Adjust f1 to the precise f for the RLC low pass filter (Step 4) resulting in minimum 1500 Hz riding on the 60 Hz signal.
2. Switch SA UP for 60 Hz input.
3. Switch SB UP for audio output from the speaker.
4. All dc and ac measurements taken with a DVOM or an FETVOM.
5. All ac voltages are to be read using a 2 μF blocking capacitor (on the panel) in series with the meter lead.
6. The 10 K volume control is to be set at full CW rotation (maximum volume.)

TABLE 1 - Normal voltage and waveforms and test conditions.

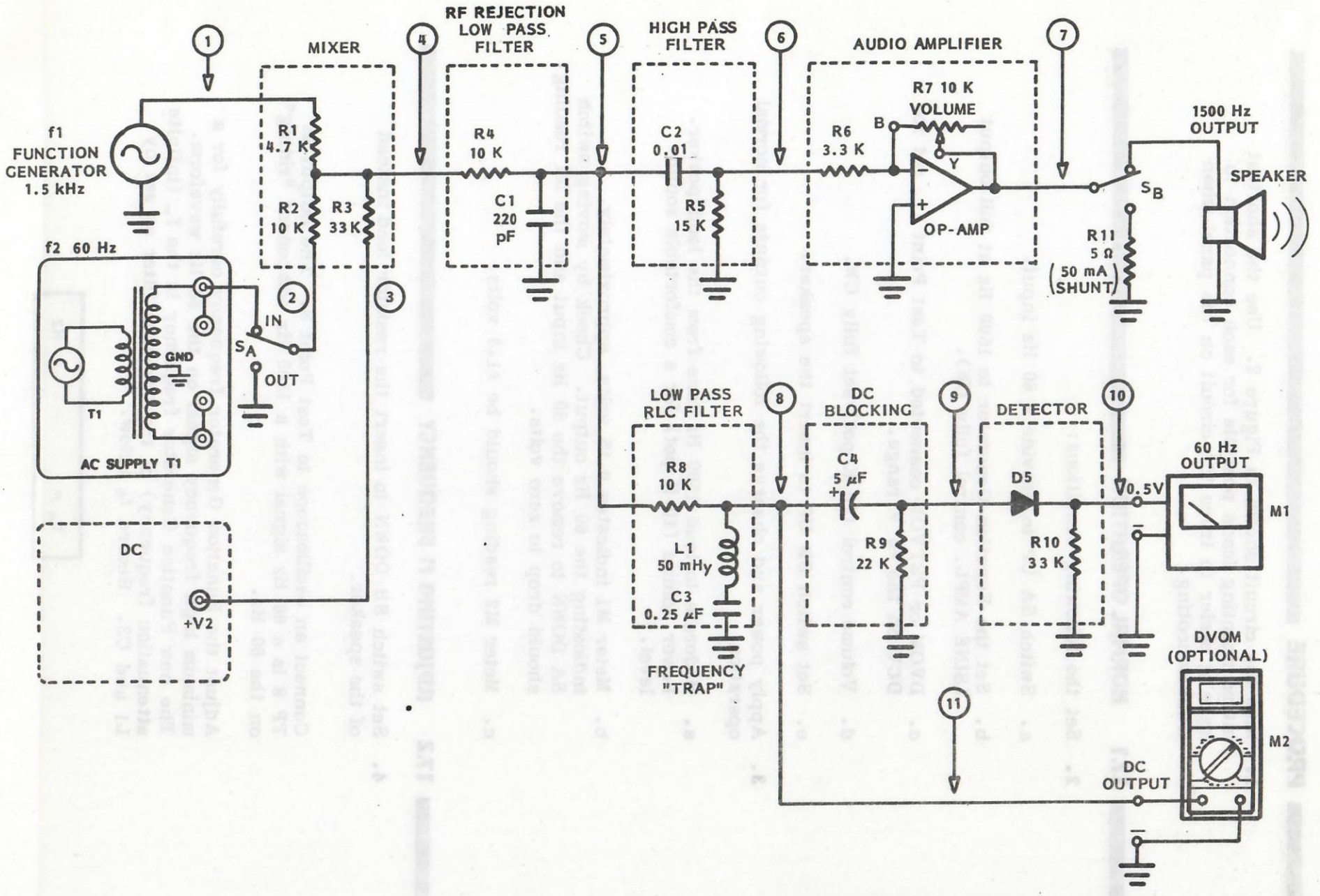


Figure 2 – Circuit to be wired for the troubleshooting EXPERIMENT.

PROCEDURE

1. Wire the circuit shown in Figure 2. Use the shortest interconnecting leads possible for each connection to make it easier to trace the circuit on the panel when troubleshooting.

17.1 NORMAL OPERATION

2. Set the following conditions:

   a. Switch SA UP to provide a 60 Hz input.

   b. Set the Function Generator to 1500 Hz at full output (SINE AMPL. control fully CW).

   c. DVOM or FETVOM connected to Test Point 11, set for DCV on the +5 V range.

   d. Volume control (10 K pot) set fully CW.

   e. Set switch SB UP to insert the speaker.

3. Apply power and observe the following outputs for normal operation:

   a. Moderate to loud 1500 Hz tone from the loudspeaker. Lower volume (10 K pot) for a comfortable sound level.

   b. Meter M1 indicates 0.15 volts, approximately, indicating the 60 Hz output. Check by moving switch SA DOWN to remove the 60 Hz input and the M1 reading should drop to zero volts.

   c. Meter M2 reading should be +1.3 volts.

17.2 ADJUSTING f1 FREQUENCY

4. Set switch SB DOWN to insert the resistor load instead of the speaker.

   Connect an oscilloscope to Test Point 8. The output at TP 8 is a 60 Hz signal with a 1500 Hz component "riding" on the 60 Hz.

   Adjust the Function Generator frequency carefully for a minimum high frequency signal on the 60 Hz waveform. The new Function Generator frequency is the f_∞ (infinite attenuation frequency) of the low-pass filter as set by L1 and C3. Record f_∞ below.

f_∞ =	Hz

17.3 DC VOLTAGE MEASUREMENTS

5. Measure the dc voltages at all the test points and list them in Table 2. Compare these voltages to those in Table 1. They should be very close in value. Be sure to follow the Test Conditions listed in Table 1 or erroneous voltages may be obtained.

TEST POINT	DCV	TEST POINT	DCV
1		7	
2		8	
3		9	
4		10	*
5		11	
6			

* Reading will drop to zero volts with SA DOWN.

TABLE 2 - Normal dc voltages for the circuit of Figure 2.

17.4 AC VOLTAGE MEASUREMENTS

6. Measure all the ac voltages as directed in the TEST CONDITIONS listed in Table 1 and enter all readings in Table 3. Compare these results to the voltages listed in Table 1.

TEST POINT	ACV	TEST POINT	ACV
1		7	
2		8	
3		9	
4		10	*
5		11	
6			

* Reading will drop to zero volts with SA DOWN.

TABLE 3 - Normal ac voltages for the circuit of Figure 2.

17.5 WAVEFORM OBSERVATIONS AND MEASUREMENTS

7. Observe each waveform on the oscilloscope as listed in Table 1. Compare the observed waveforms to those shown in Table 1 and record if they are normal or abnormal. Measure the peak-to-peak levels and record them in Table 4.

TEST POINT	WAVEFORM		P-P VOLTAGE LEVEL
	NORMAL	ABNORMAL	
1			
2			
3	X	X	0 V
4			
5			
6			
7			
8			
9			
10			
11			

TABLE 4 - Normal waveform check and p-p voltages.

17.6 TROUBLESHOOTING

8. Have your instructor insert a fault in the circuit.

9. Place switch SB UP to place the speaker in the circuit and observe the 3 outputs to see if any are not normal. Record the symptom or symptoms in Table 5. A typical symptom might be "No 1500 Hz sound output but 60 Hz and DC outputs normal."

10. Use the oscilloscope to Signal Trace from the affected output back towards the input. Record, in Table 5, the number of the Test Point you reach at which the proper signal appears.

11. List the suspect stage (block) in Table 5. You have isolated the problem to the "block" level and could replace the "plug-in card" if this were a modular unit.

12. Do not remove any wires. Run the necessary tests to determine which component is faulty. You may measure voltages across components and leads and then make resistance measurements after shutting off the power. Indicate the fault in the last column of Table 5 and list the tests that lead you to your conclusions.

13. Repeat the procedure for additional faults inserted by your instructor.

FAULT #	SYMPTOM	LAST TEST POINT	SUSPECTED BLOCK	COMPONENT FAULT AND TESTS

TABLE 5 - Troubleshooting results.

CONCLUSIONS

We have learned from this experiment that:

Simple circuits, referred to as "blocks," may be interconnected to form complex systems.

Complex systems require a systematic method to troubleshoot.

To troubleshoot a system, the technician should first be aware of the signal inputs, signal outputs and signal paths in the circuit.

One of the more frequently used troubleshooting systems is Signal Tracing.

The Test Points checked when Signal Tracing, should follow a logical sequence from the system output back to the system input.

Service Manuals are usually available for the equipment to be serviced. The manual contains circuits, normal voltages, normal waveforms and special test conditions.

ASSIGNMENT

Answer the following multiple choice questions.

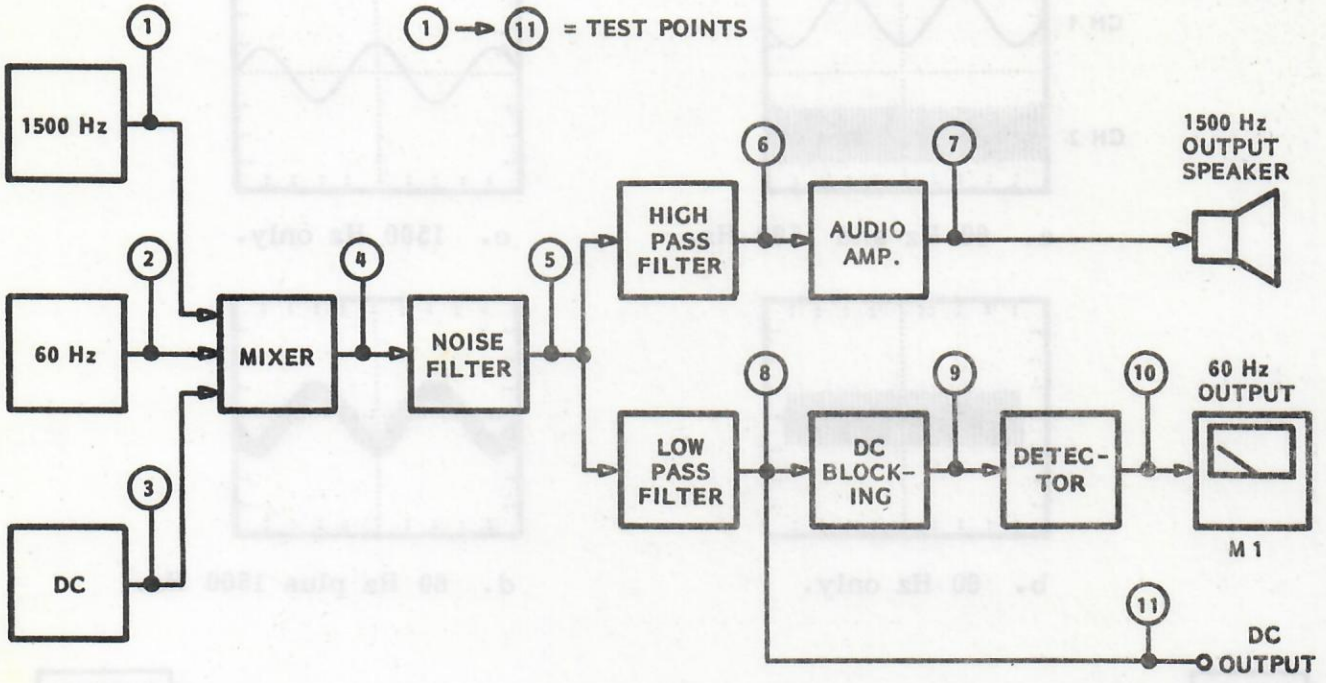


Figure 3 above refers to questions 1 to 4.

1. If no 1500 Hz output is heard from the circuit of Figure 3, the most logical sequence of test points to check is:

   a. 10; 9; 8.
   b. 5; 6; 7.
   c. 7; 6; 5; 4; 2.
   d. 7; 6; 5; 4; 1.

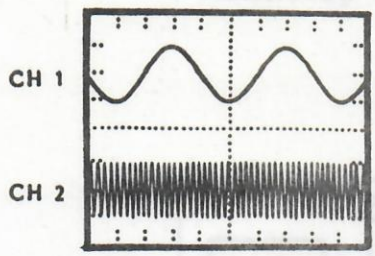
2. If no 60 Hz output is indicted on meter M1, the most logical sequence of test points to check is:

   a. 10; 9; 8; 5; 4; 2.
   b. 4; 5; 6; 8; 10.
   c. 10; 9; 8; 7; 6; 5.
   d. any of the above.

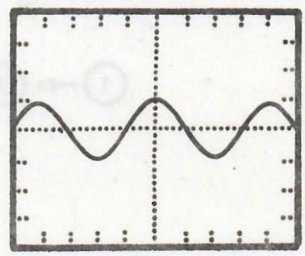
3. No dc voltage appears at Test Point 10, while Test Points 7 and 11 are normal. The fault is:

   a. too high a dc level input level.
   b. in the Detector stage.
   c. a defect in the Mixer or Noise Filter blocks.
   d. non-existent; there should be no dc at TP 10.

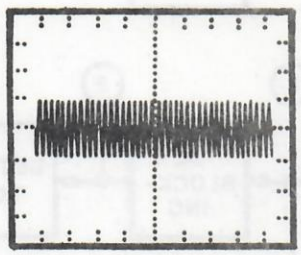
4. The waveform at Test Point 4 in Figure 3 should be:



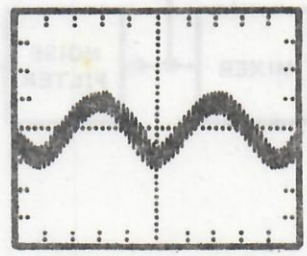
a. 60 Hz and 1500 Hz.



c. 1500 Hz only.



b. 60 Hz only.



d. 60 Hz plus 1500 Hz.

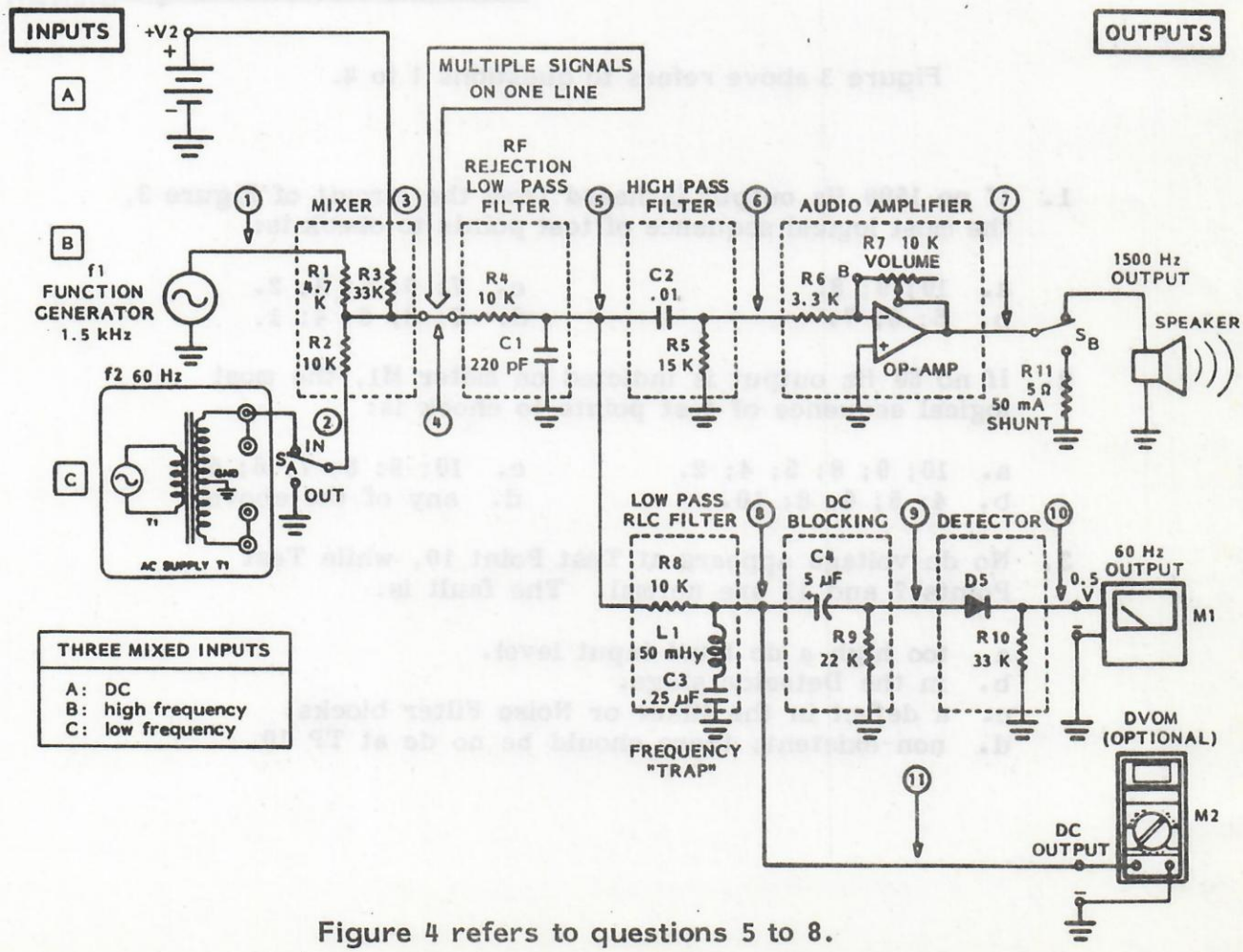


Figure 4 refers to questions 5 to 8.

5. If, at Test Point 9 in Figure 4, the voltage reading is +1.3 volts instead of the normal -0.4 volts, the most probable cause is:

   a. C4 open.
   b. C4 shorted.
   c. diode D5 shorted.
   d. resistor R10 open.

6. If at Test Point 8 in Figure 4, the level of 1500 Hz signal is very low, the:

   a. fault could be a shorted C3.
   b. wrong value inductor has been used.
   c. circuit is behaving normally.
   d. High Pass filter is trapping out the 1500 Hz signal.

7. If, in Figure 4, the normal signal is present at Test Point 6, but no output is heard from the speaker:

   a. the 10 K control is set at minimum resistance.
   b. switch SB is connected to the 5 ohms resistor.
   c. the Op-Amp circuit is defective.
   d. any of the above.

8. Placing switch SA, in Figure 4, in the DOWN position, will cause the:

   a. dc level at Test Point 11 to drop to zero.
   b. dc level at Test Point 10 to drop to zero.
   c. voltage levels at both 10 and 11 Test Points to drop to zero together.
   d. none of the above.

KEY TERMS

1. BLOCK DIAGRAM

   A diagram in which the major units that form the electronic system are drawn as blocks. The blocks are interconnected by lines, that represent wires, to show the signal paths. The direction of the signal flow is indicated by arrows and usually flows from left to right.

2. DEMULTIPLEXER

   A circuit used to separate two or more electronic signals that have been combined for transmission over a single line or pair of wires.

3. DETECTOR

   A circuit that produces a dc output that is proportional to the ac signal.

4. MULTIPLEXER

   A circuit that permits the transmission of two or more electronic signals over a single line. At the end of the transmission line the signals are separated by the demultiplexer described in 2, above.

5. NOISE FILTER

   Any undesired signals in a transmission can be defined as noise. A filter that removes these undesired signals is a Noise Filter.

6. RESISTANCE ANALYSIS

   A series of resistance measurements made at critical points in a circuit in an attempt to locate a fault.

7. SERVICE INFORMATION

   Data supplied by the equipment manufacturer that includes circuit diagrams, normal waveforms, dc and ac voltages and resistance values at different points in the circuit.

8. SIGNAL INJECTION

   A method of locating the defective stage in a system by injecting the signal into the circuit starting at the output stages and working back to the input.

9. SIGNAL TRACING

Observing or tracing the signal at each stage to locate the faulty stage. The tracing procedure is normally from the input circuit to the output circuit.

10. TEST POINT

A place in an electronic circuit at which a meaningful measurement can be made with a voltmeter, ohmmeter or oscilloscope.

11. VISUAL INSPECTION

A visual inspection of electronic equipment before starting to troubleshoot to see if there are such faults as disconnected plugs, improper assembly, broken wires, missing components, overheated components or any other fault that can be seen by eye.

12. VOLTAGE ANALYSIS

A series of voltage measurements made at critical points in a circuit in an attempt to locate a fault.